Radio Frequency Interference To DVB-T Reception From LTE Systems In Adjacent Bands

A Thesis submitted in the fulfilment of the requirements for

Masters By Research in Engineering

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This thesis is dedicated to the memory of my father, Late Chitra Bahadur Basnet, who has been my role-model for hard work, persistence and personal sacrifices, and who instilled in me the inspiration to set high goals and the confidence to achieve them.

Declaration

I, Shubhekshya Basnet certify that the work presented in this thesis is, to the best of my knowledge and belief, original, except as acknowledged in the text, and that the material has not been submitted, either in full or in part, for a degree at this or any other institution.

I certify that I have complied with the rules, requirements, procedures and policy relating to my higher degree research award of the University of Western Sydney.

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Abstract

Australians have recently benefited from the switch-over to digital television which has freed many channels called digital dividend. Australia's digital dividend is the frequency range of 694 MHz to 820 MHz which is used to operate Long Term Evolution (LTE) technology. In Australia there were 57 VHF and UHF channels used for television broadcasting. After the completion of switch-over process, UHF channels 52 to 69 were freed up which is considered as Australian digital dividend.

When LTE Frequency Division Duplex (FDD) system and digital television services operate in adjacent UHF bands, LTE FDD transmitters can cause harmful interference to digital video broadcasting-terrestrial (DVB-T). So in this study, we have presented the compatibility of operating LTE FDD services in the digital dividend spectrum identified in Australia. We have used interference analysis method to calculate the minimum separation distance between LTE FDD and DVB-T system and Monte Carlo Simulation for calculating the probability of location within considered DVB-T area that suffer maximum level of interference.

Also, there are some unused channels where digital television operates called TV White Spaces (TVWS). TVWS can be utilized to operate the secondary devices such as LTE Time Division Duplex (TDD) which helps to address spectrum scarcity issue. We have presented the study of the interference on DVB-T when LTE TDD are operating on TVWS. We have used interference analysis method to calculate minimum separation distance between LTE TDD and DVB-T. The results of our study show that increasing the guard band reduces the interference to adjacent channel.

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List Of Abbreviations

ACA: Australian Communication Authority

ACI: Adjacent Channel Interference

ACIR: Adjacent Channel Interference Ratio

ACMA: Australian Communications and Media Authority

ACLR: Adjacent Channel Leakage Ratio

ACS: Adjacent Channel Sensitivity

APT: Asia Pacific Telecommunity

BEM: Block Edge Mask

BS: Base Station

CBS: Commercial Broadcasters Services

CCI: Co-Channel Interference

CDMA: Code Division Multiple Access

CEPT: European Conference of Postal and Telecommunications Administrations

COFDM: Coded Orthogonal Frequency Division Multiplexing

CR: Cognitive Radio

DCP: Digital Channel Plan

DDS: Digital Dividend Spectrum

DFT: Discrete Fourier Transform

DFTS-OFDM: Discrete Fourier Transform Spread OFDM

DSP: Digital Signal Processing

DVB-T: Digital Video Broadcasting-Terrestrial

EDGE: Enhanced Data Rate for GSM Evolution

EIRP: Equivalent Isotropically Radiated Power

ERP: Effective Radiated Power

EU: European Union

FCC: Federal Communication

FDD: Frequency Division Duplex

FDD-FD: FDD-Full Duplex

FDD-HD: FDD-Half Duplex

FCA: Frequency Channel Assignment

FCC: Federal Communication Commission

GDB: Geolocation Database

GPP: Generation Partnership Project

GPS: Global Positioning System

GSM: Global System For Mobile

HSDPA: High Speed Downlink Packet Access

HSPA: High Speed Packet Access

IP: Internet Protocol

ISI: Intersymbol Interference

IEEE: Institute of Electrical and Electronics Engineers

LTE: Long Term Evolution

MAC: Media Access Control

MCL: Minimum Coupling Loss

OoB: Out-of-Band

PAPR: Peak to Average Power Ratio

PBS: Public Broadcaster services

PR: Protection ratio

OFDM: Orthogonal Frequency Division Multiplexing

OSA: Opportunistic Spectrum Access

QAM: Quadrature Amplitude Modulation

QPSK: Quadrature Phase Shift Keying

RFI: Radio Frequency Interference

RRC: Regional Radiocommunication Conference

RRM: Radio resource Management

SC-FDMA: Single Carrier Frequency Division Multiple Access

SDR: Software Defined Radio

SFN: Single Frequency Network

TDD: Time Division Duplex

TDMA: Time Division Multiple Access

TD-SCDMA: Time Division-Synchronous CDMA

TG: Task Group

TPC: Transmit Power Control

TRP: Total Radiated Power

TVWS: TV White Space

UE: User Equipment

UHF: Ultra High Frequency

UMTS: Universal Mobile Telecommunication System

VHF: Very High Frequency

WCDMA: Wideband Code Division Multiple Acces

WG: Work Group

WRC: World Radiocommunication Conference

WSD: White Space Device

Publications

1. S. Basnet, U. Gunawardana, S. Biyanwilage, R. Liyanapathirana,“Interference Analysis in Digital TV Reception with LTE Systems In Adjacent Bands In Australian Context”, in the Proceedings of IEEE 2014 Australasian Telecommunication Networks and Applications Conference (ATNAC), pp. 82-86, Nov 2014.

2. S. Basnet, U. Gunawardana“Interference Analysis in Digital TV Reception with LTE Systems operating in TV White Space In Australian Context” (in preparation for Submission to Australasian Telecommunication Networks and Applications Conference (ATNAC) which is being held on Sydney in 2015).

Chapter 1

Introduction

The switch-over from analogue TV to DVB-T freed up some spectrum as digital TV uses less spectrum for transmission compared to analog TV [1]. These unused spectrum that was released due to the switch-over process is called digital dividend. Digital dividend is used in all the regions for operating Long Term Evolution (LTE) systems. However, when LTE and digital television services operate in adjacent UHF bands, LTE system can cause harmful interference to television receivers and transmitters. Thus, it is necessary to evaluate the impact of operating LTE in the digital dividend frequency band on digital television receivers. It is also equally important to study the possible interference mitigation techniques to enable the co-existence of both technologies.

Australia's digital dividend is the bandwidth of 126 MHz in the frequency range of 694 MHz to 820 MHz. In Australia, it is proposed that LTE FDD system operates from channel 52 to channel 69. In FDD arrangement uplink and downlink use different frequencies. However, in Australian context LTE system will have uplink in upper side and downlink on the lower side which is referred to as conventional duplex arrangement. When LTE system operates in digital dividend, the channel 51 will be the most affected DVB-T channel.

Studies done by Australian Government Digital Switchover Taskforce [1] raised some concerns about the potential of these services to interfere with free-to-air TV signals below 694 MHz. There are two forms of interference from LTE which are the interference from LTE BS and interference from LTE UE. There are many interference studies done internationally in regards to interference from LTE system to DVB-T, some of the major studies are:

- The CEPT Report 30 [2] provides a basis for interference analysis in terms of the block edge mask (BEM) concept, which can be readily applied to the local context. The reported results are based on the Protection ratio (PR) measurements of Region 1 digital dividend and 8 MHz DVB-T channel raster, so studies needs to be done for Australian context with DVB-T channel raster of 7 MHz.

- A report submitted to the ITU-R Joint Task Group 5-6 by Free TV Australia Ltd and the European Broadcasting Union provides the best source to understand the behaviour of typical DVB-T receivers in the presence of Universal Mobile Telecommunications System (UMTS) interference in the Australian broadcasting environment. UMTS and LTE transmission is different so it is necessary to study the interference caused by LTE system through actual field measurements [3].

- Studies are done by Ofcom [4] on the reverse duplex arrangement focusing on the interference from Base Station (BS), they provided some useful informations that could be applied in Australia with conventional duplex arrangement.

TV White Spaces (TVWS) are the frequencies in the DVB-T spectrum that are not been utilized by DVB-T broadcasting system. These varies according to locations and time. White spaces can be utilised by secondary users which will increase the spectrum efficiency and open door for many other new services. White space device (WSD) can operate in TVWS subject to no interference to primary users. There are two types of WSD which are fixed WSD with high transmission power and portable WSD with low transmission power. WSD should use the cognitive radio (CR) technology to sense the unused spectrum based on current location and time and then choose the unused channel according to their need [8]. In Australia TVWS exists in the DVB-T operating frequencies ranging from 520 MHz to 694 MHz. When WSD device operates in TVWS it may cause harmful interference to adjacent DVB-T channels.

1.1 Problem Statement

Australia's digital dividend is the frequency range of 694 MHz to 820 MHz that is from channel 52 to channel 69. When LTE FDD services are deployed in digital dividend, the channel 51 will be the most affected television channel. Channel 51 lies in the frequency range of 687 MHz to 694 MHz. The impact of operating LTE FDD in digital dividend will be investigated in this thesis. This can be evaluated by studying the minimum separation distance between LTE FDD and DVB-T and probability of location that suffer unacceptable level of interference within considered DVB-T area.

TVWS may vary according to location and time. TVWS can be utilized to solve increasing spectrum scarcity issue by operating secondary users in TVWS. The main issue when allowing secondary users to broadcast from TVWS is the interference to DVB-T. LTE TDD is considered as secondary user. The another problem this thesis try to address is the impact of operating LTE TDD in TVWS. This can be evaluated by calculating the minimum separation distance between LTE TDD and DVB-T system so that the interference from LTE TDD does not deteriorate the reception of DVB-T.

1.2 Major Contributions

This thesis has resulted in several contributions towards digital dividend study in Australia. The major contributions are as follows:

- The protection distances between LTE FDD and DVB-T operating on adjacent bands is calculated for Australia taking into account Australian digital dividend and frequency arrangements.

- The outage probability for considered DVB-T area is calculated that suffer unacceptable levels of interference when LTE FDD operates in adjacent band.

- A study on interference analysis methods for LTE TDD and DVB-T is carried out, when LTE TDD is operating in TV White Space for frequency Arrangement in Australia.

1.3 Thesis Organisation

The remainder of thesis is organised as follows:

Chapter 2 presents a detailed literature review which introduces Digital video broadcasting -terrestrial, Long Term Evolution, digital dividend, channel and frequency arrangement concepts. Digital dividend for Australia are discussed in more details followed by channel arrangements. Conventional duplex arrangement for frequency is explained along with Asia Pacific Band plan.

In Chapter 3, interference analysis from LTE FDD to DVB-T is presented. Firstly, interference analysis method is performed to analyse the minimum separation distance between LTE FDD and DVB-T. Secondly, probability of locations within the considered area is calculated that suffer unacceptable level of interference. Lastly results are shown for both calculations.

In Chapter 4, TV white space (TVWS) is studied. TVWS in Australia is explained followed by regulating white space usage, white spaces and channel planning, white space arrangements and the guard bands. Interference analysis is performed to calculate the minimum separation distance between DVB-T and LTE TDD when LTE TDD is operating on TV white space.

Chapter 5 concludes the thesis by providing a summary of the research work, its outcomes, and possible directions for future research.

Chapter 2

LITERATURE REVIEW

Recently Australia's switchover from analog to digital TV has been accomplished successfully. The spectrum needed by digital television for broadcasting is minimum in regards to analog TV, due to which some unused spectrum will be freed. With the use of these freed frequencies, spectrum scarcity issues can be resolved which leads towards the development of broadcasting and communications sectors [9].

2.1 Digital Video Broadcasting-Terrestrial

Digital video broadcasting-terrestrial (DVB-T) transmits and receives television using digitally compressed signal compared to long established analog transmission. DVB-T is one of the most preferred standards for the transmission of terrestrial televisions. Digital television also allows broadcasters to provide a greater range of features such as multichannels, high definition television (HD TV) and an electronic program guide (EPG). These standards were first published in 1997 and transmission of first DVB-T started in UK in November 1998 [10].

According to Digital video broadcasting [11] studies "DVB-T system transmits compressed digital audio, digital video and other data in an MPEG transport stream, using coded orthogonal frequency-division multiplexing (COFDM or OFDM) modulation. DVB-T offers three different modulation schemes (QPSK, 16QAM, 64QAM). DVB-T as a digital transmission delivers data in a series of discrete blocks at the symbol rate. DVB-T is a COFDM transmission technique which includes the use of a Guard Interval. It allows the receiver to cope with strong multipath situations. Within a geographical area, DVB-T also allows single-frequency network (SFN) operation, where two or more transmitters carrying the same data operate on the same frequency. In such cases the signals from each transmitter in the SFN needs to be accurately time-aligned, which is done by sync information in the stream and timing at each transmitter referenced to GPS. The length of the Guard Interval can be chosen. It is a trade off between data rate and SFN capability. The longer the guard interval the larger is the potential SFN area without creating intersymbol interference (ISI). It is possible to operate SFNs which do not fulfil the guard interval condition if the self-interference is properly planned and monitored."

As most countries worldwide Australia has already switched to digital TV. Digital terrestrial television in Australia was launched on 1 January 2001, in the country's five most populous cities, Sydney, Melbourne, Brisbane, Adelaide and Perth. Australia uses DVB-T system which is used in Europe, Russia, India and many other countries. The Minister for Broadband and Communications had set the date as part of the national digital switch-over which was planned by 2013 [11]. Analog television services in Australia used five designated broadcasting service bands

(VHF-I, VHF-II, VHF-III, UHFIV and UHF-V), While digital television uses only three bands (VHF-III, UHF-IV and UHF-V). A total of 50 channels (8 VHF Band III and 42 UHF) are used to provide digital services. Analog television services in Australia used to operate on VHF channels 0 to 12 and UHF channels 28 to 69 where as DVB-T services operate from channel 6 to channel 51 [12].

According to Australian broadcasting Authority the technical planning for digital terrestrial television in metropolitan and regional areas of Australia was based on a number of key requirements and assumptions [12].

- It was the requirement for the analog mode to digital mode conversion that broadcasters achieve the same level of coverage in standard definition TV digital mode as soon as practicable after the commencement of the simulcast period so that viewers who currently receive the service will continue to have access to television services after the end of simulcast period.
- Broadcasters need to transmit a high definition TV version of the service in digital mode. This leads to high data rate requirement, which means planning must be based on a digital broadcasting system and operational mode that can achieve the required data rate.
- Digital television is planned for operation within existing allocated broadcasting service bands (i.e. Bands III, IV and V).

2.1.1 Channel Planning

Channel planning for DVB-T was done initially assuming some transmission parameters to study the interference between the services. According to Digital planning handbook [12] the primary objectives in developing the digital channel plan (DCP) were:

- Avoid or minimise interference and disruption to analog television reception.
- Identify the channels that could be used for digital services at sufficient ERP levels to achieve the same level of coverage, from the same transmission sites, as the analog services.
- Plan the most efficient use of the spectrum.
- Minimise cost to viewers and broadcasters.

Channel allotments in DCP's were proposed by studying the compatibility of transmitting the DVB-T and other services in the similar geographical location. In the certain geographical location the wanted and unwanted signals were assessed and comparison was done between wanted signal level, unwanted signal level and noise level. According to Digital planning handbook [12] the method for assessing compatibility is described below:

- Propagation predictions and use of statistical methods

  According to Digital planning handbook [12]"A range of propagation models are available to predict wanted and unwanted field strengths or signal levels which vary from empirical models through to diffraction based models such as Millington, Deygout and Epstein-Peterson. All propagation models are subject to some degree of uncertainty because of simplifying assumptions in the models and limitations in the accuracy of topographic and other data used for calculations. In broadcast planning, the characteristics of the propagation channel are generally not well known. For these reasons it is usual to employ statistical methods in the prediction and modelling of signal coverage and interference."

- Antenna Height

  The height of transmit and receive antenna are really important in predicting any propagation model. According to Digital planning handbook (2005) for digital channel planning the height of transmit antenna was assumed similar to the analog TV and the height of receiver antenna was considered to be 10 m above the ground [12].

- Nuisance field

  The result of harmful interference from the transmitter in the coverage area of the wanted transmitter is the nuisance field [12]. According to Digital planning handbook (2005) the nuisance field describes the quantitative interference effect of a transmitter on the coverage of wanted transmitter. It is derived from the predicted field strength of the interfering transmitter, the applicable protection ratio and the receive antenna height directivity and polarisation discrimination.

- Polarisation and receiving antenna discrimination

  According to technical planning parameters [14] receiving antenna discrimination due to polarisation or directivity shall not be taken into account in the planning of services.

- Continuous and tropospheric interference

  According to Digital planning handbook [12] when a source of potential interference does not vary distinctly with time it is called continuous, where as in situations where the potential interference is not continuous in nature, whether as a result of long distance propagation effects or other intermittent conditions, it is said to be tropospheric.

2.2 Long Term Evolution

Long Term Evolution (LTE) is the latest generation of mobile technology that is currently in use. In LTE, data transmission is done from use equipment (UE) to base station (BS) in uplink whereas in downlink from BS to UE [14]. LTE achieves peak data rates of more than 100 Mbps over the downlink and 50Mbps over the uplink; improved coverage- that is high data rates with wide area coverage; the potential to significantly reduce latency in the user plane in the interest of improving the performance of higher layer protocols as well as the delay associated with control plane procedures; and greater system capacity-threefold capacity compared to current standards [14].

LTE supports both frequency division duplex (FDD) and time division duplex (TDD), as well as wide range of system bandwidths in order to operate in a large number of different spectrum allocations [15]. LTE system in its downlink uses Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple access in its uplink. The bandwidths that LTE supports are 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz [16].

2.2.1 Single Carrier Frequency Division Multiple Access

SC-FDMA is the technique utilized by the LTE uplink for transmission. SC-FDMA is the slightly changed form of OFDM and is aslo called Discrete Fourier Transform Spread- OFDM (DFTS-OFDM). SC-FDMA is more beneficial in uplink transmission due to low peak to average power ratio (PAPR). SC-FDMA allows for the possibility of low complexity but high quality equalization in frequency domain and it is also possible to have flexible bandwidth assignments with SC-FDMA [17] .

Another benefit of SC-FDMA is the so called 'built-in' frequency diversity. Because SC-FDMA spread the information of one symbol through all the available sub carriers, so in case losing partial information on one (or even more) subcarriers due to deep fading does not necessarily lead to losing the information modulated in the symbol. Figure 2.1 shows the block diagram of SC-FDMA transmitter and receiver [18].

SC-FDMA divides the transmission bandwidth into multiple parallel subcarriers maintaining the orthogonality of the subcarriers by the addition of cyclic prefix as a guard interval. However, in SC-FDMA data symbols are not directly assigned to each subcarrier independently like in OFDMA. Instead, the signal which is assigned to each subcarrier is a linear combination of all modulated data symbols transmitted

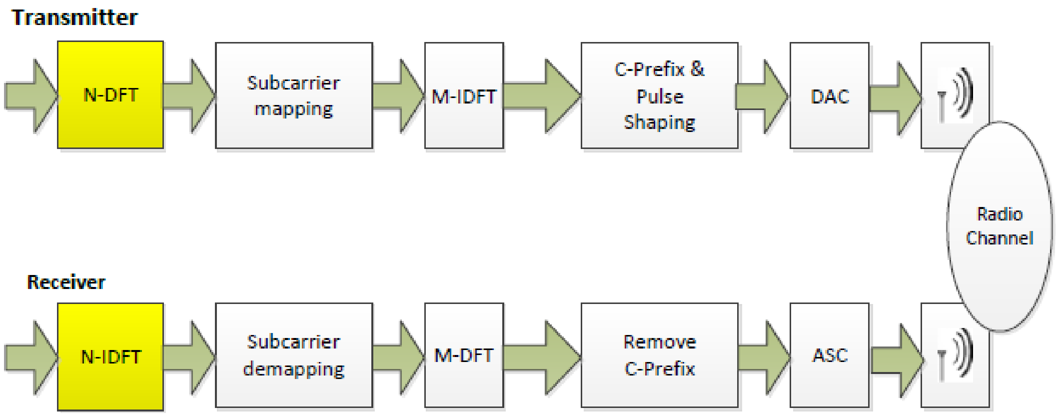

Figure 2.1: Block diagram of transmitter and receiver of SC-FDMA

at the same time instant [19].

2.2.2 Orthogonal Frequency Division Multiplexing

Orthogonal frequency-division multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies. OFDM has developed into a popular scheme for wideband digital communication, whether wireless or over copper wires, used in applications such as digital television and audio broadcasting, DSL broadband internet access, wireless networks, and 4G mobile communications. OFDM works by splitting the radio signal into multiple smaller sub-signals that are then transmitted simultaneously at different frequencies to the receiver. 802.11a WLAN, 802.16 and WiMAX technologies use OFDM [20].

OFDM is a specialized FDM, the additional constraint being all the carrier signals are orthogonal to each other. In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other, meaning that cross-talk between the sub-channels is eliminated and inter-carrier guard bands are not required. This greatly simplifies the design of both the transmitter and the receiver; unlike conventional FDM, a separate filter for each sub-channel is not required. Future telecommunication systems must be spectrally efficient to support a number of high data rate users. OFDM uses the available spectrum very efficiently which is very useful for multimedia communication [20].

Orthogonality makes it possible in OFDM to arrange the sub carriers in such a way that the sidebands of the individual carriers overlap and still the signals are received at the receiver without being interfered by ICI. The receiver acts as a bank of demodulators, translating each subcarrier down to DC, with the resulting signal integrated over a symbol period to recover raw data [20]. Studies done by N. Marchetti et. al [20] shows that some other benefits of OFDM are :

- The beauty of OFDM lies in its simplicity. One trick of the trade that makes OFDM transmitters low cost is the ability to implement the mapping of bits to unique carriers via the use of IFFT.

- Unlike CDMA, OFDM receiver collects signal energy in frequency domain, thus it is able to protect energy loss at frequency domain.

- In a relatively slow time-varying channel, it is possible to significantly enhance the capacity of adapting the data rate per subcarrier according to SNR of that particular subcarrier.

- OFDM is more resistant to frequency selective fading than single carrier systems.

- The OFDM transmitter simplifies the channel effect, thus a simpler receiver structure is enough for recovering transmitted data. If we use coherent modulation schemes, then very simple channel estimation is needed, on the other hand, we need no channel estimator if differential modulation scheme are used.

- The orthogonality preservation procedure in OFDM are much simpler compared to CDMA or TDMA techniques even in very severe multipath condition.

- OFDM can be used for high speed multimedia application with low service cost.

- OFDM can support dynamic packet access.

- Single frequency networks are possible in OFDM, which is specially attractive for broadcast applications.

- Smart antenna can be integrated with OFDM. MIMO systems and space time coding can be realized on OFDM and all the benefits of MIMO systems can be obtained easily.

2.2.3 Frequency Division Duplex and Time Division Duplex

Frequency division duplex (FDD) is the approach in which in which one frequency band is utilised for the transmission of information and other one utilised for receiving information. In FDD, one frequency spectrum is designated for the uplink to transmit data from UE to the BS, while another band of frequency spectrum is designated to the downlink to transmit data from the BS to UE. Guard bands are use to separate uplink and downlink. In FDD, BS transmits in one frequency band and UE in other so there will be no interference between UE and BS. ADSL and VDSL, most cellular systems, including the UMTS/WCDMA and the cdma2000 system, IEEE 802.16 WiMax also uses frequency division duplexing mode [21].

Time Division Duplex (TDD) is a approach in which uplink and downlink uses the same frequency for transmission of data but are separated by time. Each user uses one or two time slots for the uplink and downlink. Studies done by I. Poole [21] shows that the guard time is necessary to reduce the interference between two separated time slots designated for uplink and downlink which may lead to delay within the network.

2.2.4 Problems in Cellular Mobile Communication

Cellular system interference is one of the key features in increasing the capacity. According to S. Miah [24] there are many sources of interference like base station transmitting in the same frequency band, another mobile user in same cell, a call in progress in neighbour cell, impairments caused by the propagation of radio waves etc., but the most crucial ones are Co-Channel Interference (CCI), Adjacent Channel Interference (ACI), Inter-symbol Interference (ISI), Fading and Thermal Noise [23].

Co-Channel Interference (CCI) is the interference due to co-channel cells is called CCI. CCI can be reduced with minimum separation distance to maintain acceptable isolation caused by propagation distance [24].

Adjacent channel interference (ACI) is caused when two different channels are in adjacent frequency and either of them is causing interference to the other. ACI can be reduced with the use of filter and selecting channels in different frequency range [24].

2.3 Digital Dividend

Switchover from analog to digital television will free some valuable spectrum called the digital dividend and will provide services more efficiently and effectively. Transmission of digital services requires less frequency compared to the analog TV which leads to more channels in less spectrum. The purposed end for switchover from analog to digital TV was 17 June 2015 by Regional Radiocommunications Conference (RRC-06). However, few countries requested for switchover period to increment by five years [5]. In Australia switchover to digital TV was completed on December 2013.

According to B.Modlic et. al [5] "The size of the digital spectrum available for TV and radio services in each country has been identified in the digital plan established as part of the Geneva 2006 Agreement (RRC-06). This agreement defines the number of "coverage layers" that countries have been allocated for the provision of DVB-T and T-DAB services in frequency bands III and IV/V. Although "coverage layers" have been allocated for broadcast services, it is possible for national administration to allocate frequencies for other types of services as long as they do not require more protection or cause more interference than allowed in the plan."

The World Radiocommunications Conference which was held in 2007 (WRC-07), divided the world in three different regions which were Region 1, 2 and 3. Europe, Middle East, Africa and Russia lies in Region 1, The Americas in Region 2 and countries like Australia, Japan and New Zealand in Region 3.
Figure 2.2 shows ITU: Region 1, 2 and 3 Studies done by A. Guidotti et. al [31] shows that the digital dividend of Region 1 lies in the frequency range of 790 MHz to 960 MHz and for Region 2 in the frequency range of 69 MHz to 960 MHz. According to digital dividend green paper [6] digital dividend for Japan will be of 60 MHz in the frequency above 710 Mhz and New Zealand's digital dividend will be 112 MHz in the frequency range of 694 MHz to 806 MHz.

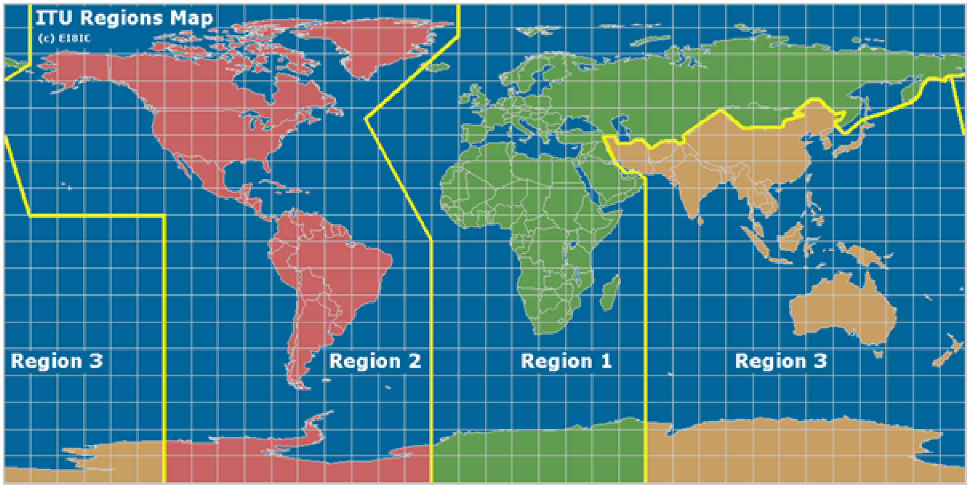

Figure 2.2: ITU: Region 1, 2 and 3 [31]

2.3.1 Frequency Arrangement

The European Commission issued the second mandate to European Conference of Postal and Telecommunications Administrations (CEPT) on technical consideration regarding harmonisation options for the digital dividend in the European Union. It included common and least technical conditions in the band 790-862 MHz [32].

According to CEPT 23 [32] to achieve a harmonised solution while maintaining the required flexibility for administrations regarding the non-mandatory introduction of mobile communication applications in the band 790-862 MHz, the following principles have been applied:

- Common frequency arrangements have been defined, to the greatest extent possible, to facilitate roaming, border coordination and to achieve economies of scale for equipment, whilst maintaining the flexibility to adapt to national circumstances and market demand.
- All duplex methods TDD, FDD full duplex (FDD-FD) and FDD half duplex (FDD-HD) have been initially considered with the aim to define a solution to accommodate spectrum for operators who would wish to use different technologies, while paying due attention to coexistence issues and spectrum efficiency.
- The time frame for availability of the band for mobile/fixed communications networks and future technology evolution has been taken into account to define location and size of the duplex gap.
- Careful consideration has been given to the block sizes for the band plans.
- Recognizing the advantage of a single harmonised frequency arrangement, the preferred frequency arrangement is based on FDD. TDD and other approaches can be used on a national basis.
- The trade off between increasing the frequency separation at 790 MHz and reducing the duplex gap has been carefully studied. In weighing up this trade off it has been decided that the frequency separation should be 1 MHz and

the duplex gap 11 MHz.

- The implementation of the frequency arrangement by national administrations will require coordination with any other administration whose broadcasting service and/or other primary terrestrial services are considered to be affected. For broadcasting, the coordination procedure would be pursuant to the GE-06 agreement.

2.3.2 LTE Bands

The Asia-Pacific Telecommunity (APT) band plan is also called band 28 by 3rd Generation Partnership Project (3GPP). This is the distribution of frequency in the range of 698 MHz to 806 MHz which is also called 700 MHz band. All the operators around the world are interested in this APT700 MHz band plan for the deployment of LTE system. Studies done by M. Vanston [26] showed that APT700 band was developed by Australia and New Zealand and was widely accepted by many other countries. Australia and New Zealand is not affected by the interference from neighbouring countries like in South East Asia. APT700 band plan benefits not only the supporting ecosystem, but also simplifies inter-country spectrum co-ordination and resolves cross border interference [26].

South Asian Telecom Regulatory Council (SATRC) is a work area within APT which includes regulatory bodies from Afghanistan, Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan and Sri Lanka. APT700 band plan was adopted on 16th March 2013. According to M. Vanston [26] during SATRC 14th council meeting (SATRC-14), representatives of the nine member countries (with the exception of Iran and Sri Lanka) announced their commitment to working as equal partners in order to fulfil the tremendous potential of the APT700 MHz Band Plan and to accelerate transition from analog to digit al broadcast TV services in 700 MHz band (where applicable) which will free up this spectrum for its highest value use, which is mobile broadband [26].

2.3.3 Reverse Duplex Arrangement

The preferred approach in European Union (EU) countries for the arrangement of freed spectrum is the reverse duplex arrangement. In the reverse duplex arrangement the downlink lies in the lower part and uplink in the upper part. According to AWF-9/OUT-12 [27] extensive studies done in Europe have shown a significant level of interference from the mobile services base station (BS) out-of-band (OOB) emissions to the DVB-T reception. Some of these studies have also analysed the possible interference from mobie services user equipment (UE) on the DVB-T reception below 790 MHz.

According to W. Sami [33] the reason for choosing reverse duplex arrangement in Region 1 countries are listed below:

- Adjacent Channel Interference from UE to DVB-T should be minimised at short distance. The interference from UE is harder to foresee and reduce than that of BS. Increasing the frequency separation by adopting the reverse duplex reduces this risk.

- A need to reduce the risk of adjacent channel interference from DVB-T high power transmitters into reception of uplink signals at the mobile service BS. This is achieved by maximising the frequency separation between DVB-T and the mobile uplink channels.

- The guard band between the downlink and adjacent DVB-T channel is less compared to mobile uplink and DVB-T, to provide satisfactory technical conditions and achievable reduction measures.

Preferred harmonized chanelling arrangement for the band 790-862 MHz in Europe

790-791	791-796	796-801	801-806	806-811	811-816	816-821	821-832	832-837	837-842	842-847	847-852	852-857	857-862
Guard band	Downlink						Duplex gap	Uplink					
1 MHz	30 MHz (6 blocks of 5 MHz)						11 MHz	30 MHz (6 blocks of 5 MHz)					

Figure 2.3: Preferred Harmonized Channelling Arrangement For The Band 790-862 MHz In Europe [33]

2.3.4 Conventional Duplex Arrangement

The frequency arrangement in which uplink is in the lower part and downlink is in the upper part is the conventional duplex arrangement. According to AWF-9 meeting [27] the conventional duplex arrangement is the approved procedure for allocating the freed spectrum in Region 3 countries. Figure 2.4 illustrates the harmonised conventional duplexing band plan for 698-806 MHz band.

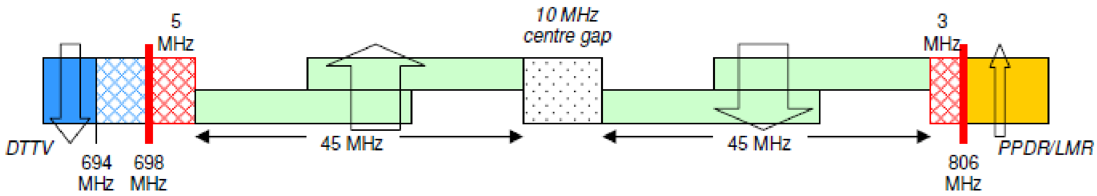

Figure 2.4: Harmonised FDD Arrangement of 698-806 MHz Band [28]

Based on AWF-9 meeting [27] the results on the interference to DVB-T due to conventional duplex arrangement using Monte Carlo Simulation is "The mobile uplink makes a significant level of interference on DVB-T reception. Even with an 8 MHz guard band, the interference probability would be about 1% to 1.4% that corresponds up to about 5% to 10% loss in broadcast coverage area".

According to CEPT23 [29] the interference reduction procedure for conventional duplex arrangement are:

- Reducing the OoB emission limits of UMTS mobile terminals.
- Limiting the maximum transmit power of mobile terminals to as level that minimises the risk of overloading DVB-T receiver front ends.
- Improving the receiver characteristics of future DVB-T receiver.

2.4 Digital Dividend in Australia

In Australian context, the studies done by Kordia Pty Ltd and ACMA had found that restacking of broadcasting services would release a contiguous block of 126 MHz belonging to the spectrum in the upper UHF band 694-820 MHz [6]. Australia recently benefited from completion of switchover procedure releasing frequency spectrum which is being utilized by LTE system. According to B. Hanta [19] the process involved in releasing digital dividend in Australia is listed below:

- Digital Switchover (completed in December 2013)

  This process involved the switching of analog television and turning on the digital TV which lead to free some parts of spectrum previously utilized by analog TV.

- Spectrum Reallocation (completed in December 2014)

  This process includes the authorisation of the digital dividend spectrum which was primarily used by broadcasting services to be re-licensed and allocated for new uses.

- Auction (completed in May 2013)

  The digital dividend auction was held in April-May 2013 to offer the freed spectrum to market.

- Channel Changes and Television Retune (completed in December 2014)

  Last step was to utilise the freed spectrum by LTE system. The process also included reorganizing the digital transmission below UHF frequency of 694 MHz.

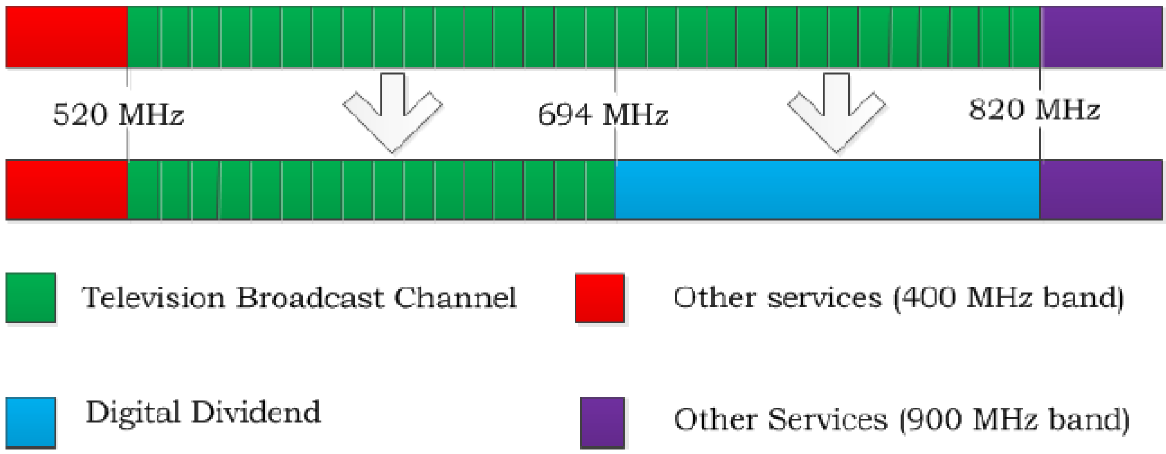

Figure 2.5: Current Digital Dividend Arrangement

Figure 2.5 shows the arrangement for the 520 to 820 MHz frequency spectrum which is utilised for the television broadcasting and the arrangement after the restack is completed on December 2014. Digital dividend spectrum for mobile service (4G) in Australia was available from 1 January 2015.

Figure 2.6 shows the graphical representation of the frequency arrangements in the digital dividend. There is a guard band 9 MHz wide at the end of the digital dividend. This is to provide some protection to the active digital dividend frequencies

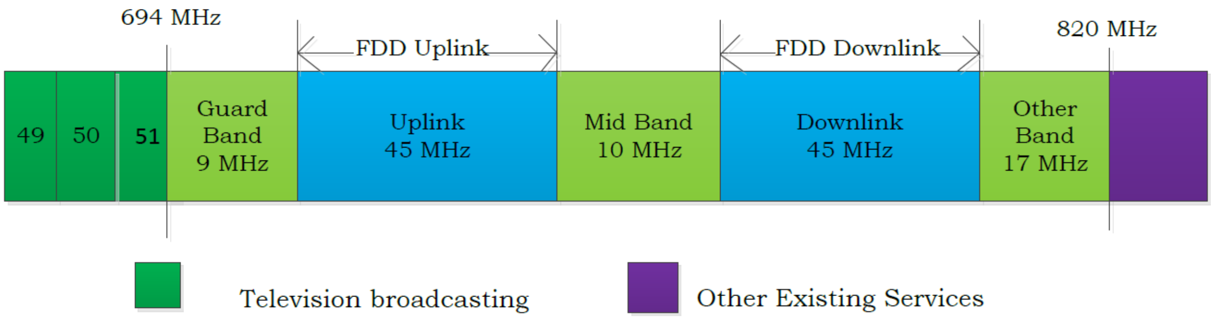

Figure 2.6: Make Up Of Digital Dividend

from interference from adjacent services. The two blue line show the uplink block of frequencies, 45 MHz wide and the downlink block of frequencies, also 45 MHz. Uplink is the signal from mobile device to base station and downlink is the signal from base station to mobile device. There is a mid band gap of 10 MHz, shown in green, between these two blocks. This is to protect the two blocks from interfering with each other.

2.4.1 Digital Dividend Auction in Australia

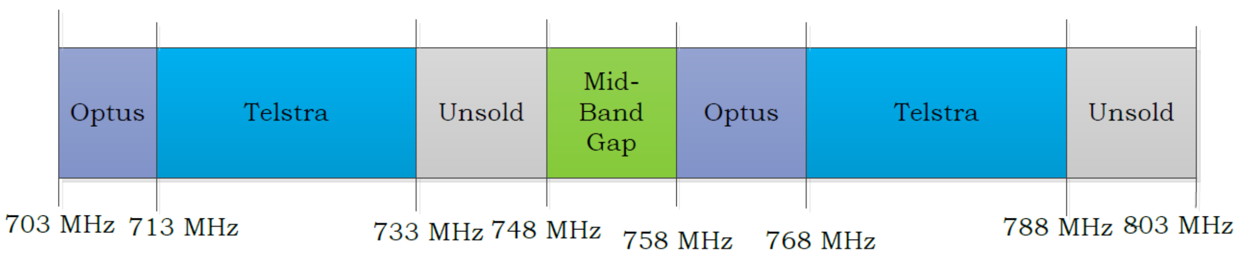

Figure 2.7: Frequency Ranges Assigned To Successful Bidders In Australia

Auction for Digital Dividend in Australia started from late April and concluded in May 2013 for 700 MHz and 2500 MHz band. A total of 90 MHz (2×45 MHz) within the 700 MHz band was allocated for wireless communications as part of auction. The result for spectrum auction showed two successful operators, Telstra with 2×20 MHz (40 MHz) and Optus with 2×10 MHz (20 MHz). The spectrum was allocated to bidders as shown in Figure 2.7.

2.5 Radio Frequency Interference

The emission or transmission of radio frequency energy which is produced by electrical and electronic devices that will cause harmful interference to other equipments is the radio frequency interference. Radio-frequency signal to interference (C/I) ratio, is generally expressed in dB, of the power of wanted signal to the total power of interfering signals and noise, evaluated at the receiver input. The power of the wanted signal is measured in a bandwidth equal to the wanted signal bandwidth, while the total power of interfering signal and noise is measured in a bandwidth equal to the interfering signal bandwidth [14].

2.5.1 Block Edge Mask

The block edge mask (BEM) approach, which consist of in block and OoB limits depending on the frequency offset. The out-of-block (OoB) component of BEM consists of a baseline limit as well as transitional (or intermediate) limits, to be applied, where applicable, at the frequency boundary of an individual spectrum licence. These limits were derived using studies of appropriate compatibility and sharing scenarios between ECN and other applications in adjacent bands but in same geographical area. It should be understood that BEM do not always provide the required level of protection of victim services and in order to resolve the remaining cases of interference additional mitigation techniques would need to be applied [2]. Considering cellular like topology as the most likely implementation in the 790-862 MHz band, two different BEMs have been developed for BS and UE. According to CEPT Report 30 the BEM for UE transmission states that [2]:

- The require UE OoB baseline limit for the protection of outdoor DVB-T reception is -50 dBm/8 MHz for frequencies below 790 MHz and the limit for in-block total radiated power (TRP) is 23 dBm.

The in-block EIRP limit for the BS may be specified by the administration based on compatibility studies and deployment requirements. Further, it is emphasised that the defined BEM limits do not always provide the required level of protection and additional mitigation techniques would also need to be applied. It has been shown that [2]:

- The uplink guard band required to protect DVB-T fixed reception from UE transmission is around 7 MHz with additional filtering at the DVB-T receiver, while a guard band of 12 MHz or greater would require without additional filtering.

Simulation result demonstrate that the TV receiver failure rate does not improve significantly with the reduction in BS BEM baseline below 0 dBm/8 MHz for high EIRP of the BS ($\geq$ 59 dBm/10 MHz). However, for lower EIRP levels, this failure rate shows a significant improvement with a reduction in the ECN BS BEM baseline. Simulation results also show that [2]:

- For all UE carrier frequencies centred at 807 MHz and above, the number of locations where a TV would suffer unacceptable performance is approximately 1% with and without UE present.

- The filtering in the DVB-T receiver reduces interference at carrier frequencies 797 MHz and 802 MHz; however, the performance is still unacceptable at 797 MHz.

2.5.2 Protection Ratio And Overloading Threshold

Protection Ratio (PR) is the minimum value of the signal to interference ratio required to obtain a specified reception quality under specified conditions at the receiver input. PR is specified as a function of the frequency offset between the wanted and the interfering signals over a wide frequency range. PR curves show the ability of a receiver to discriminate against interfering signals on frequencies differing from that of wanted signal [34].

Overloading threshold is the interfering signal level expressed in dBm, above which the receiver begins to lose its ability to discriminate against interfering signals at frequencies differing from that of the wanted signal. Therefore, above the overloading threshold the receiver will behave in a non-linear way, but does not necessarily fail immediately depending on the receiver and interference characteristics [34].

According to ITU-R BT.2215-2 [34] protection ratios and overloading thresholds of a receiver strongly depend on the frequency and time domain characteristics of the interfering signal used in the measurements. Therefore, it is necessary to record the power spectral density, the adjacent channel leakage power ratio as well as the amplitude as function of time of the interfering signal. The protection ratios are generally considered and used as independent of the wanted signal level. That is C/I is supposed to be a linear function with unity slope. The protection ratio of the receiver is obtained by subtracting I from C/I at any points on this line and can be used for all wanted signal levels. However, the measurement results show that in most cases the protection ratios of wideband TV receivers vary as a function of wanted signal level. Consequently, C/I is not a straight line with unity slope with some variation with the interfering signal strength. Nevertheless, for interfering signals below the overloading threshold such C/I curves can always be approximated by a straight line with unity slope with an acceptable error. This method has been used for determining the PR of DVB-T receivers [34].

2.5.3 Adjacent Channel Leakage Power Ratio and Adjacent Channel Sensitivity

Adjacent channel leakage ratio (ACLR) is a measure of transmitter performance. It is the ratio of an interfering transmitter's mean power within its assigned channel to its mean power within an adjacent channel [33].

Adjacent channel sensitivity (ACS) is a measure of receiver performance. It is the ratio of the received power from a given source in an assigned channel (in-channel) to the received power from a given source in an adjacent channel (out-of-channel) which passes through the receive filter [33].

In the Figure 2.8, the out-of-block signal (P1) falling in the DVB-T channel gets

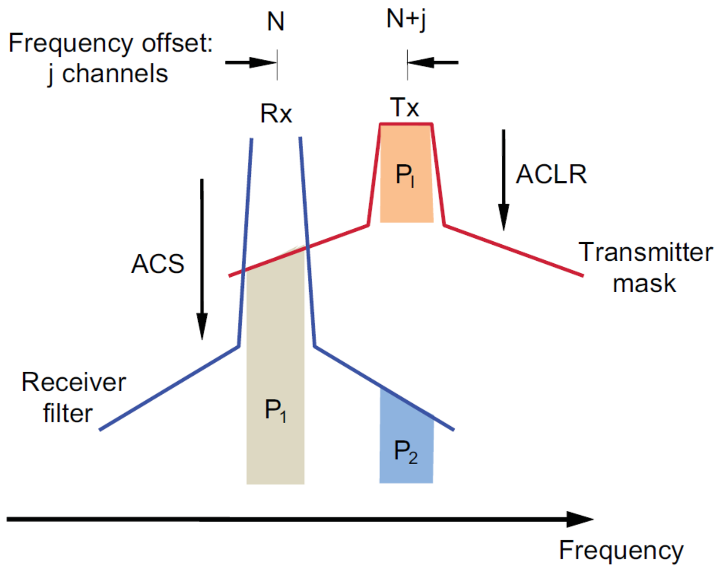

Figure 2.8: ACLR And ACS [33]

into the DVB-T receiver without any attenuation whereas the in-block signal of the case station (Pl) gets into the DVB-T receiver after being attenuated by the selectivity of the receiver (P2). Interference occurs when the ratio of signal to total power resulting from these two components and noise at the receiver input falls below the minimum required level [33].

Chapter 3

Interference Analysis From LTE to DVB-T

In this chapter, the impact on DVB-T by the interference from LTE FDD devices operating on digital dividend is analysed. In chapter 2 details of digital dividend in Australian context was provided. We will be evaluating the minimum separation distance between LTE FDD and DVB-T and outage probability on considered DVB-T coverage area, taking data from chapter 2 for Australian context.

To protect the DVB-T network reception, it is important to ensure that the maximal interference reduction is obtained when a specific channel/frequency is assigned to a DVB-T transmitter. This is one of the main goals of broadcast network planning. There are two parameters that are crucial in achieving this goal [35]:

- Minimal Usage Field
- Minimal signal to interference ratio

The values for the minimal usage field for the DVB-T system are specified in the ITU recommendation BT.1368-8 [69]. The minimal signal to interference ratio (C/I) is also called protection ratio (PR) and it is crucial for achieving the reception of the signal and proper decoding procedures. If the harmful interference level is above the wanted signal level on the receiver input, the reception will not be possible. The reception is possible when the minimal usage field strength is for the value of protection ratio above the interference signal level. If this condition is not met, the picture quality will degrade very fast.

The DVB-T system uses Coded Orthogonal Frequency Division Multiplexing (COFDM). In accordance with network requirement there are several parameters that can be set in the COFDM: carrier modulation, code rate and guard interval. A combination of these parameters is called DVB-T system variant. The choice of the system variant depends on the network planning process. Each of the system variants has its own protection ratio, minimal usage fields and maximal data rates [35].

3.1 Interference Analysis Method

The interference scenario where an outdoor TV receiver antenna is interfered by outdoor UEs is considered as shown in Figure 3.1. We will consider both LTE FDD UEs and Base Station (BS) interference on to DVB-T.

In order to assess the interference, the most affected channel of DVB-T, Channel

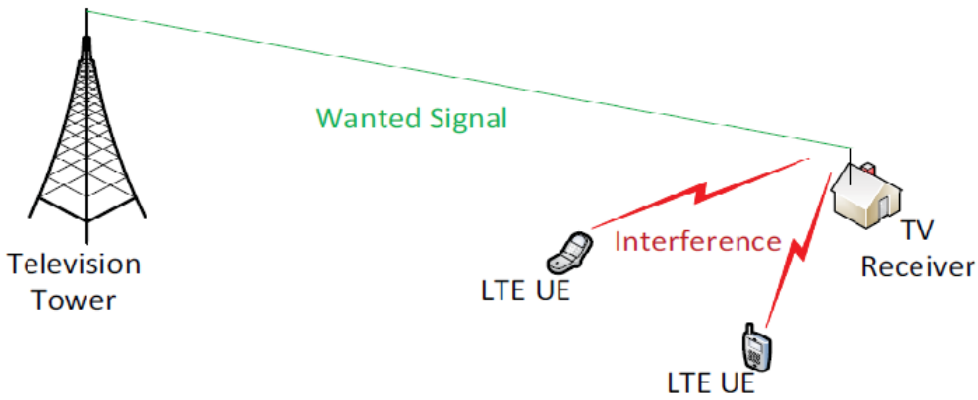

Figure 3.1: Interference from LTE-UEs on TV Receiver

51 in the spectrum between 687 and 694 MHz with the centre of frequency of 690.5 MHz is taken into consideration. It is assumed that the DVB-T signal is received at the required minimum median field strength levels calculated for different environments in accordance with the Australian DTTB Planning Handbook [12].

The values in Tables 3.1 and 3.2 shows DVB-T and LTE parameters which are used for performance evaluation.

Table 3.1: DVB-T transmitter parameters

Parameter	Value
ERP (dBm/7 MHz)	73 and 63
Receiver antenna gain (dBi)	9
Antenna height (m)	100

The interfering LTE FDD service is operating in the conventional duplex mode above 703 MHz with a guard band of 9 MHz as shown in Figure 3.2. LTE FDD uplink and downlink bandwidths are 1.4, 3, 5, 10, 15 and 20 MHz.

Table 3.2: LTE Parameters [13]

Parameter	Type	Value
LTE maximum transmit power (dBm)	UE	23
	BS	43
Noise figure (dB)	UE	9
	BS	5
Bandwidth (MHz)		1.4, 3, 5, 10, 15, 20
Antenna height urban (m)	UE	1.5
	BS	30
Antenna height rural (m)	UE	1.5
	BS	45
Antenna gain (dB)	UE	0
	BS	15

As the first study, we analyse the minimum separation distance between LTE FDD UEs or BSs and DVB-T receiver antenna so that the interference from the LTE FDD UEs or BSs do not deteriorate the reception of DVB-T signal.

The total interference from LTE FDD system to DVB-T can be expressed as [36]:

$$I_{LTE-FDD} = P_t + G_{tr} + G_{re} - ACIR - PL \tag{3.1}$$

where, $I_{LTE-FDD}$ = total channel interference received from LTE FDD,

P_t = Transmit power of LTE FDD system,

G_{re} = DVB-T receiver antenna gain,

G_{tr} = LTE FDD antenna gain,

PL = the propagation path loss between DVB-T receiver and LTE FDD.

Adjacent channel intereference ratio ($ACIR$), is the total interference between adjacent channels. $ACIR$ depends solely on adjacent channel selectivity (ACS) and

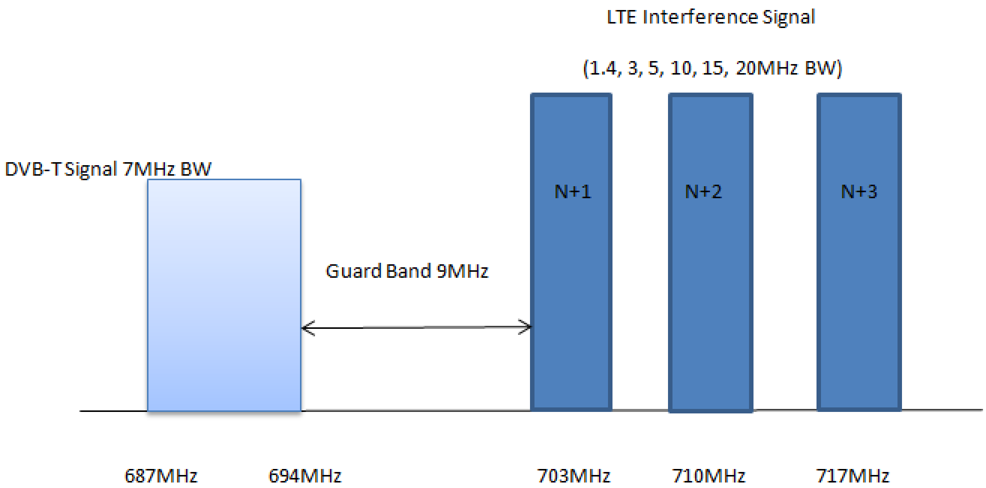

Figure 3.2: Desired Signal and Interference Signal Frequency Arrangement

adjacent channel leakage ratio ($ACLR$) performance numbers. It can be expressed as [36]:

$$\frac{1}{ACIR} = \frac{1}{ACS} + \frac{1}{ACLR} \tag{3.2}$$

In the case of uplink, $ACLR_{UE} << ACS_{BS}$ as the UE transmitter is the limiting design factor which dominates the uplink interference. So in an uplink simulation $ACIR \approx ACLR_{UE}$ where UE $ACLR$ performance is simulated [40].

In the case of downlink, $ACS_{UE} << ACLR_{BS}$ as the UE receiver is the limiting design factor which dominates the downlink interference. So in downlink simulation $ACIR \approx ACS_{UE}$ where UE ACS performance is simulated [40].

$ACIR$ can be calculated using guard bands which is expressed as [41]:

$$ACIR = P_{inband} - 10 \times \log_{10}(P_t \times BW(10^{(-1.8 \times G + 10^{-4}})) \tag{3.3}$$

where,P_{inband} is the power of operating band in dBm,
G is the guard band,
P_t is the transmitting power in mW,
BW is the bandwidth in MHz.

To prevent interference from LTE FDD to DVB-T, the interfering signal power should be controlled as the following inequality [36]:

$$I_{LTE-FDD} < I_{th} \tag{3.4}$$

where, I_{th} is the interference threshold of LTE FDD transmitter of BS or UE and is taken to be an I_{th}/N value of 6 dB [37].
To satisfy $I_{LTE-FDD}$<I_{th}, it needs to maintain a minimum distance or isolation between DVB-T and LTE FDD BS or UE.

The receiver noise which is expressed as N can be obtained as follows [36]:

$$N = -174 + 10 \log_{10}(BW) + NF \tag{3.5}$$

where, BW is the LTE FDD bandwidth and NF is the noise figure.

When the distance between DVB-T transmitter and LTE FDD BS or UE is fixed, additional isolation should be guaranteed to protect DVB-T from the interference signal of LTE, which can be expressed as follows [36]:

$$I_{LTE-FDD} - I_{add} < I_{th} \tag{3.6}$$

ACS is a measure of receivers ability to receive a signal at its assigned channel frequency in the presence of modulated signal in the adjacent channel. ACS is calculated using the power of wanted signal and maximum power of interference under a fixed bit error rate of receiver measured in the test which is obtained as follows [36]:

$$\frac{P_{refsen}}{N_t} = \frac{P_{refsen} + \triangle s}{N_t + 1/ACS} \tag{3.7}$$

where, P_{refsen} is sensitivity power level,

N_t is thermal noise of receiver and

△s is the ratio of wanted signal power to receiver sensitivity.

Path loss (PL) is expressed in dB. The path loss can be calculated using the formula [36]:

$$PL = 69.55 + 26.16 \log_{10}(f) - 13.82 \log_{10}(H_{BS}) a(H_{UE}) + [44.9 - 6.55 \log_{10}(H_{BS})] \log_{10}(d) \tag{3.8}$$

where,

$$a(H_{UE}) = [1.1 \log 10(f) - 0.7] H_{UE} [1.56 \log 10(f) - 0.8], \tag{3.9}$$

d is the separation between transmitter and receiver ,

f is a centre frequency,

H_{BS} = Base station antenna height,

H_{UE} = User station antenna height.

Now we can use (3.1) and (4.8) to determine the minimum separation distance (d_{min}) which provide the necessary isolation between DVB-T antenna and LTE FDD transmission. The resulting minimum separation distance can be expressed as:

$$d_{min} = 10^{\frac{(P_t+G_{tr}+G_{re}-ACIR-I_{LTE-FDD}-69.55-26.16\log_{10}(f)+13.82\log_{10}(H_{BS})+a(H_{UE})}{[44.9-6.55\log_{10}(H_{BS})]}} \tag{3.10}$$

3.2 Outage Probability Analysis

In this section we will study the probability of locations within the coverage area of a DVB-T transmitter that will suffer unacceptable levels of interference from LTE system. For DVB-T to operate properly signal to interference plus noise ratio (SINR) should be greater than acceptable SINR level.

Outage probability analysis is performed considering area of 40 m from DVB-T receiver where both DVB-T and LTE cellular network. For this analysis, the DVB-T coverage area is divided into 10 annular rings of equal area (Area-1, Area-2,...,Area-10) and the DVB-T receiver is randomly located within each annular ring as shown in Figure 3.3. In Figure 3.3. an annular ring is the area between circles with radius r_1,..r_i,..,R_{TT}. It is assumed that the TV receiver suffers unacceptable interference when its signal to interference ratio (SINR) [2, 39] falls below about 20 dB. The OoB emissions are taken according to the LTE standards [42]. A comprehensive analysis of outage probability is illustrated in CEPT report 30 [2]. Our analysis is based on CEPT report 30 [2].

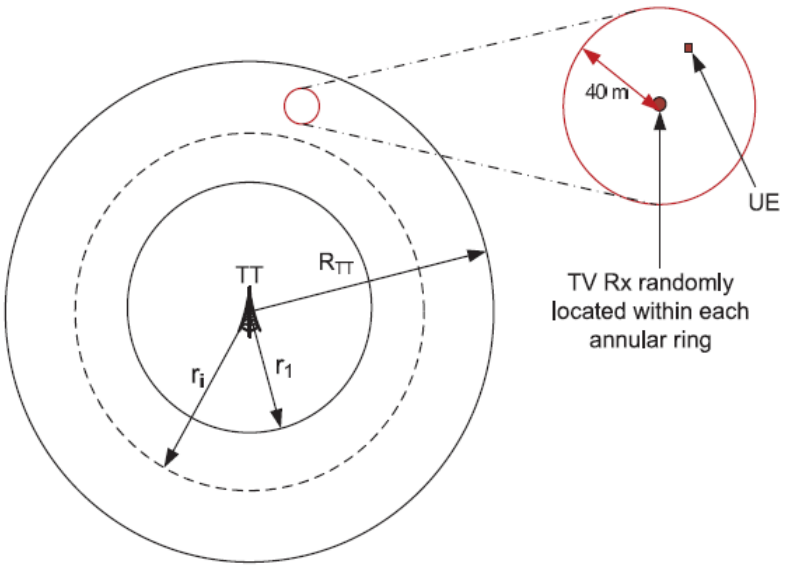

Figure 3.3: Probability of Outage Locations

The outer radius of each annular ring is proportional to square root of the are of circle within. The outer radius of each annulus is related to the overall radius of the LTE system coverage area as follows:

$$r_i = r_o \times \sqrt{\frac{10-i}{10}} \tag{3.11}$$

where r_o is the radius of LTE coverage area, i is the number of each annulus, where i=0 for the outer annulus i=9 for the inner most annulus.

The area of each annulus is

$$a_i = \pi(r_i^2 - r_{i-1}^2) \tag{3.12}$$

To calculate the average path-loss for each annulus we calculate the average range of all locations within the annulus. This is the radius where the area within the annulus is equal for all locations outside and outside this radius. This is given by:

$$r_{i,PL} = r_o \times \sqrt{\frac{(10-i)}{10} - 0.01} \tag{3.13}$$

The average wanted signal power (LTE system to TV) in each annulus is given by [2]:

$$P_{i,S} = P_{TT} + G_{i,PL(LTE,DVB_T)} + G_{A,(DVB-T)} + g_{\phi,(DVB-T)}\delta\phi + g_{\xi,(LTE)}\delta\xi \tag{3.14}$$

where,

$g_{\phi,DVB-T}$ is the DVB-T antenna directional pattern as a function of elevation of ϕ,

$g_{\xi,LTE}$ is the LTE antenna directional pattern as a function of elevation ϕ,

$\delta\phi$ is the elevation offset of DVB-T receiver from bore sight of DVB-T antenna,

$\delta\xi$ is the elevation offset of LTE from bore sight of LTE antenna,

The average adjacent channel interference power (P_{AC}) from the LTE system into the DVB-T channel is given by the LTE out-of-block baseline ($P_{OOB,(TS)}$) plus the (worst-case) path-gain between the LTE system and the DVB-T ($G_{PG,(TS,TV)}$) plus the body loss of the LTE (G_{BL}).

$$P_{AC} = P_{OOB,(TS)} + G_{PG,(TS,TV)} + G_{BL} \tag{3.15}$$

The average in-band interference power ($P_{I,CC}$) from the LTE system into the DVB-T systems adjacent channel is given by the LTE in-band power ($P_{IB,(TS)}$) plus the total (worst-case) path-gain between the LTE system and the DVB-T ($G_{PG,(TS,TV)}$) plus the body loss of the LTE (G_{BL}) minus the DVB-T ACS for the relevant frequency offset [2].

$$P_{I,CC} = P_{IB,(TS)} + G_{PG,(TS,TV)} + G_{BL} - ACS \tag{3.16}$$

The average SINR for each annulus is given by :

$$SINR_i = P_{i,S} - 10\log_{10}(10^{P_{AC}/10} + 1 + 10^{P_N/10} \tag{3.17}$$

The percentage of locations ($L\%$) within each annulus where the SINR is less than the 20 dB interference threshold is calculated as follows :

$$L\% = 1 - f\left(SINR_i - \frac{20}{\sigma_{SINR}}\right) \tag{3.18}$$

where, $f()$ is the standard normal cumulative distribution function, and σ_{SINR} is the standard deviation of the $SINR$, given by [2]:

$$\sigma_{SINR} = \sqrt{\sigma^2_{TT,TV} + \sigma^2_{TS,TV}} \tag{3.19}$$

where, $\sigma_{TT,TV}$ is the standard deviation of the wanted link (5.5 dB) and $\sigma_{TS,TV}$ is the standard deviation of the interfering link (3.5 dB).

The TV receiver is supposed to function correctly if :

$$SINR = \frac{P_s}{P_N + P_{I,Intra} + P_{I,CC} + P_{I,AC}} \geq SINR_T \tag{3.20}$$

where,

$SINR$ = Signal-to-interference-plus-noise ratio at DVB-T receiver,

$SINR_T$= Target SINR at DVB-T receiver,

P_S = Wanted DVB-T signal power at DVB-T receiver,

$P_{I,Intra}$= Intra-system interference power at DVB-T receiver,

$P_{I,CC}$= Co-channel interference power at DVB-T receiver,

$P_{I,AC}$= Adjacent-channel interference power at DVB-T receiver.

Detailed calculation of $P_{I,Intra}$, $P_{I,CC}$ and $P_{I,AC}$ are explained in CEPT report 30 [2]. Now it is possible to vary $\sigma_{TT,TV}$ and $\sigma_{TS,TV}$ around the expected value using a normal distribution. Then a Monte-Carlo simulation is performed to estimate the probability of location where $SINR$ is greater than $SINR_T$.

3.2.1 The Results Of Interference Analysis Method

Table 3.3 shows the results of interference analysis method which shows the required minimum separation distance between LTE FDD UE to DVB-T for different LTE FDD bandwidths for rural and urban environments. The results for UE indicates that the protection distance should be more than 2.31 cm for urban and 2.85 cm for rural scenarios to prevent the interference from LTE FDD UE to DVB-T receiver antenna.

Table 3.4 shows the results of interference analysis method which shows the required minimum separation distance between LTE FDD BS to DVB-T for different LTE FDD bandwidths for rural and urban environments. The results for BS indicates that the protection distance should be more than 1.741 m for urban and 2.15 m for rural scenarios to prevent the interference from LTE FDD BS to DVB-T receiver antenna.

Table 3.3: Minimum Separation Distance Between FDD LTE UE to DVB-T

LTE BW (MHz)	ACIR (dB)	I_{th} (dBm)	Minimum Separation distance (cm)	
			urban	rural
1.4	183.53	-97.538	2.31	2.85
3	180.22	-94.228	2.31	2.85
5	178	-92.010	2.31	2.85
10	**174.99**	**-89**	**2.31**	**2.85**
15	173.23	-87.239	2.31	2.85
20	**171.98**	**-85.989**	**2.31**	**2.85**

Table 3.4: Minimum Separation Distance Between FDD LTE BS to DVB-T

LTE BW (MHz)	ACIR (dB)	I_{th} (dBm)	Minimum Separation distance (m)	
			urban	rural
1.4	160.53	-101.538	1.74	2.15
3	157.22	-98.228	1.74	2.15
5	155	-96.010	1.74	2.15
10	**151.99**	**-93**	**1.74**	**2.15**
15	150.23	-91.239	1.74	2.15
20	**148.99**	**-89.989**	**1.74**	**2.15**

In Australia, Telstra acquired two lots of 20 MHz blocks and Optus acquired two lots of 10 MHz blocks in 700 MHz band. Given that, in Australian context most likely LTE deployments in digital dividend would be 10 MHz and 20 MHz bandwidths which are highlighted in Tables 3.3 and 3.4. Figure 3.5 shows the variation of minimum separation distance with LTE bandwidths for rural and urban environment.

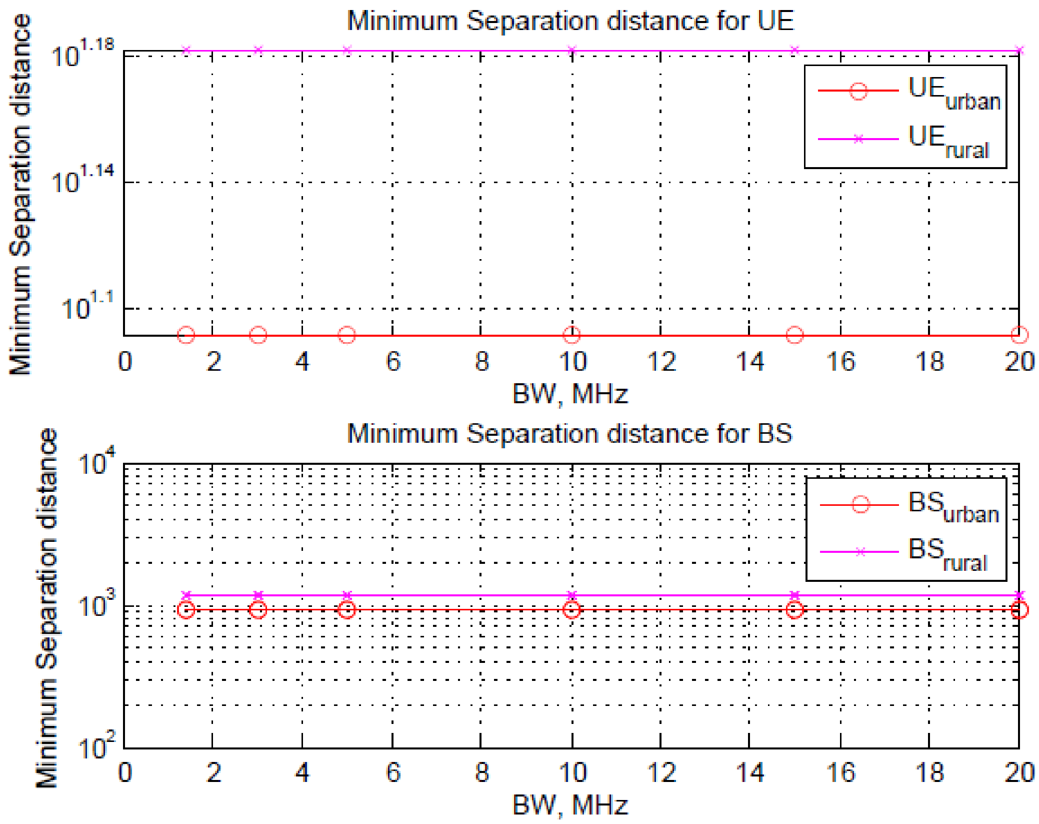

Figure 3.4: Minimum Separation Distance Between LTE UE or BS and DVB-T

A previous study shows that a larger separation is required in both urban and rural environments (30 km in rural and 800 m in urban) when LTE is considered to be operating from 695 MHz [39]. In our study we have evaluated the impact of interference from LTE FDD when operating from 703 MHz with the guard band of 9 MHz. The results show that with the incresed guard band the minimum separation distance between LTE FDD and DVB-T is reduced significantly.

3.2.2 Results Of Outage Probability Analysis

Figure 3.5 shows the percentage of locations affected by the UE transmission when the DVB-T transmitter antenna height is 100 metres and the coverage area is 25 km. Accordingly, the probability of locations affected by the UE transmission is very signifcant towards the edge of the coverage area. The percentage of locations affected by UE which shows the percentage of affected locations is higher for low power DVB-T broadcasting in the presence of guard band of 9 MHz. Area 1, Area 2,..Area 10 refer to area of 10 annular rings as explained in Section 3.2.

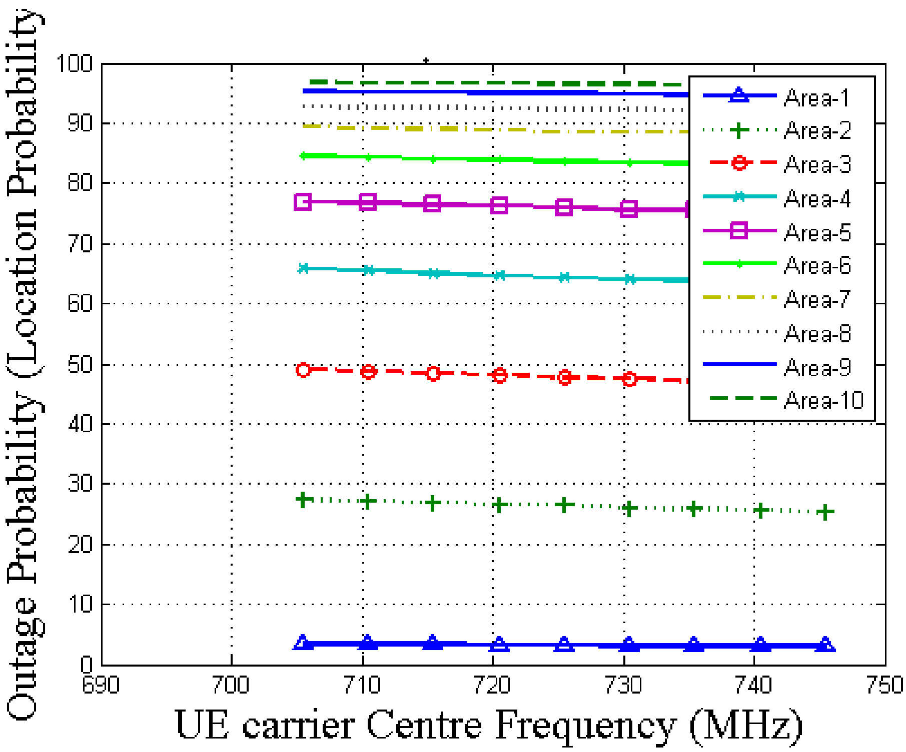

Figure 3.5: Probability of Outage Locations

3.3 Summary

In this study we focus on the interference analysis between LTE FDD UE or BS to DVB-T in the Australian context with the presence of a guard band of 9 MHz between DVB-T and LTE FDD uplink using Interference analysis method and Outage Probability Analysis. The results show that increasing the guard band between LTE FDD UE or BS and DVB-T reduces the interference between adjacent channels and minimum separation distance reduces with the increase in guard band. The results of our study show that there is a minimum interference onto DVB-T reception on channel 51 when LTE system is operating on adjacent channel in digital dividend spectrum.

Chapter 4

TV White Space

4.1 Introduction

TV White Space (TVWS) is the unused spectrum between the channels assigned for digital TV broadcasting. TVWS vary according to geographical location and time. With the increasing demand for spectrum these TVWS can be beneficial to many other applications with low interference. Some TVWS applications are wireless microphone, IEEE802.11af and LTE. Cognitive Radio (CR) is the underline technology that enables TVWS services.

Although there have been many studies on use of TVWS, only two countries currently have regulations permitting unlicensed use of TVWS: the United States and the United Kingdom [53, 56]. The FCC has established TVWS in both the VHF and UHF bands, whereas in the United Kingdom only UHF is allowed. In the United States each TV channel is 6 MHz wide, whereas channel width in the United Kingdom is 8 MHz [56].

4.2 Cognitive Radio

Cognitive radio is one of the latest developments in the field of telecommunication. With the increasing demand for spectrum, cognitive radio technology has been developed to address the spectrum shortage issue by utilising the spectrum more efficiently [62]. Cognitive radio technology is able to select the frequency band, the type of modulation, and power levels most suited to the requirements, prevailing conditions and the geographic regulatory requirements [65].

In CR technology users are categorized as licensed users and unlicensed users. The licensed users have absolute rights to get access to the spectrum at any time, while the unlicensed users take advantage of the spectrum only when the licensed users are absent. The built in spectrum holes detection strategy of unlicensed users make them switch over to other vacant channels immediately when the licensed users return [65]. The main properties of CR are [63][64]:

- To detect the unused spectrum by digital terrestrial television and utilize the spectrum without causing harmful interference to primary users.
- CR should be able to operate on the most suitable free spectrum that meets the transmission requirement.
- CR should be able to change the transmit specifications according to the need in that geographical location.

Figure 4.1 shows the cognitive radio cycle. CR sense the unused spectrum by considering the activities by primary users and the transmit power in that area. Then the unused spectrum is analysed and CR will choose one of the spectrum based on transmission parameters required in that radio environment and start the transmission from that spectrum.

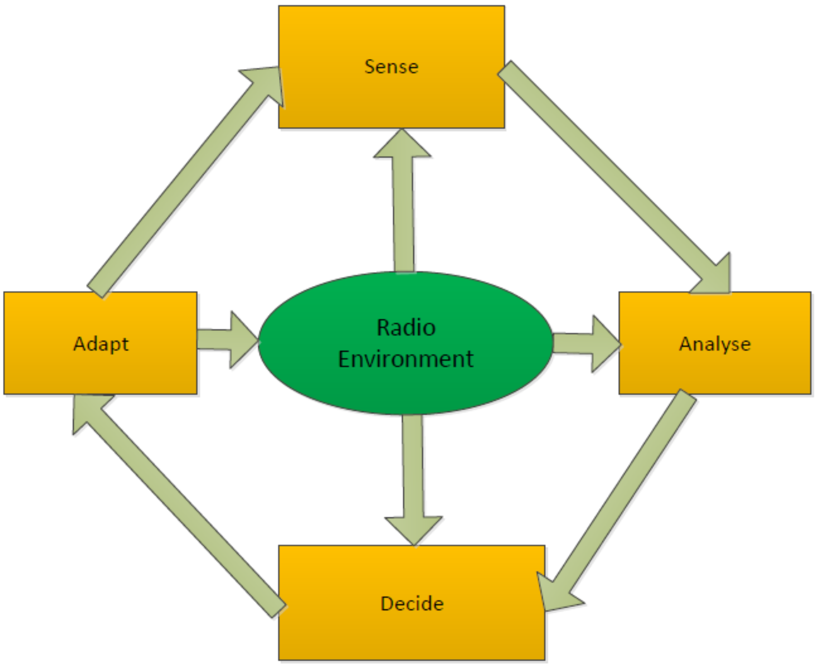

Figure 4.1: Cognitive radio cycle

4.3 White Space Device

The goal of TV white space devices (WSD) is to address spectrum scarcity problem by operating on TV white spaces. However, when WSD operates in TVWS the main issue would be to protect the DVB-T (primary users) from interference caused by WSD. To protect the primary users from unwanted interference, WSD relies on Cognitive radio technology. That is WSD should have the ability of sensing and geo-location database systems. WSD should find out the radio signals and estimate the position of the DVB-T to protect primary users from interference [58].

It is possible for a WSD to use a geolocation database system to find out currently unused spectrum in given location and time. This technology is preferred by the US regulator Federal Communication Commission (FCC) and Ofcom in the UK, it is currently under development by commercial companies [51] [53]. To determine which unused spectrum to use, WSD communicates with database systems to get informations such as unused spectrum and suitable transmit power for that location. Once all these informations are received by WSD, it selects one of the unused spectrum and operate in that channel [51].

A secondary user can use the unused TV spectrum provided it does not cause harmful interference to the TV band users and it relinquishes the spectrum when a primary user (such as TV Transmitter) starts operation. Since the availability of TV white spaces vary with location and time, secondary service operators are interested in the amount of available white space. The available TV white space depends on regulations such as the primary user protection margin, maximum height above average terrain, secondary user power, and the separation distance [53]. TVWS in United States lies in the frequency range of 54 MHz to 698 MHz and 470 MHz to 790 MHz in Europe [54].

There are two types of WSD, which are fixed WSD and portable WSD. Fixed WSD have high transmit power and transmission is done from fixed locations. However, portable WSDs perform transmission from various different locations and have low transmit power. Standards are under review however some recommended specifications by C. Sum et. al [55] are fixed devices are permitted to transmit up to a 4 W equivalent of EIRP, with 1 W output power and a 6 dBi gain antenna per channel. On the other hand, personal/portable devices are permitted to transmit up to 100 mW equivalent EIRP, with no antenna gain; except that when operating in a channel adjacent to an incumbent licensed user and within the protected area of that service, the allowable transmit power is limited to 40 mW. Besides the average power across the entire channel, there is also a spectral density constraint of 12.6 dBm and 2.6 dBm per 100 kHz for fixed and personal/portable devices. Sensing-only personal/portable devices are allowed to transmit up to 50 mW [55].

4.3.1 IEEE802.11af

IEEE 802.11af is one of the smaller task groups (TG) within IEEE 802.11 work group (WG) which is responsible for legalizing wireless local area network communications in TVWS [55]. The IEEE 802.11af Task Group (TG) within the IEEE 802 Working Group (WG) was created in January 2010 to define modifications to the

802.11 physical (PHY) and medium access control (MAC) layers to meet the legal requirements for channel access and coexistence in the TV white spaces (TVWS) [52]. Specifically, IEEE 802.11af modifies IEEE 802.11ac (VHT very high throughput) radio to create an IEEE 802.11 standard that meets the TVWS requirements [52].

The only difference between IEEE 802.11af and IEEE 802.11 principles is the geolocation database. IEEE 802.11af includes a geolocation database, which is used to record the geographical location of unused channel in which WSD are allowed to perform their transmission from and the parameters WSD should work with in that location to meet the regulatory requirement [54]. The geolocation databases (GDB) are authorized and administrated by regulatory authorities; therefore, a GDBs operation depends on the security and time requirements of the applied regulatory domain [54].

4.3.2 LTE in TV White Space

The frequency which is not been used by digital TV can be utilized to operate the LTE systems in TVWS. A wider TVWS band lies in lower frequency band i.e. 520 MHz to 694 MHz in Australia [59]. TVWS has really good propagation properties that can be beneficial to telecommunication sector. In particular, the much lower frequencies occupied by TV spectrum (e.g., under 700 MHz, compared to Wi-Fi operating at 2.4 GHz or above 5 GHz) imply that signals can carry over much longer distances and propagate much better through obstructions such as foliage and building walls. This is expected to translate to a significantly lowered cost-of-coverage, as fewer base stations will be required to establish a widearea coverage footprint. Since propagation in urban canyons and indoor penetration have been historical challenges to wireless broadband, the opening up of lower frequency spectrum has been greeted with considerable excitement. White space frequencies also include good non-line-of-sight propagation characteristics as well as low industrial noise and reasonable antenna sizes for fixed and nomadic broadband applications. Thus, LTE deployment in white space promises innovation and growth [66]. That means if LTE can utilize the TVWS for transmission, it is possible to have faster internet speeds, lesser black spots as overcrowding in networks can be reduced.

Making TV white space bands available for unlicensed use has opened a new and very promising market to meet this demand for broadband wireless services and products. It is attractive as it is both non-disruptive to existing services and it creates an opportunity for small or regional operators who generally would have a difficult time acquiring adequate licensed spectrum [66].

To operate LTE systems on TVWS, LTE UE designed to operate on white space should be used. When LTE system operates on TVWS it should first check for unused spectrum where digital TV operates and select one of the suitable spectrum which is not been used to operate on. During this process LTE UEs will be identifying the unused channel and sending continuous information to base stations. The BS will be collecting and combining these information and based on that BS will decide whether UE can utilize the same channel for transmission or change. Secondly, the BS with a geolocation database should be used to assign the free channel to LTE UE. BS need to check the geolocation database every 24 hours [66].

When the LTE system operates on TVWS physical layer should be able to easily modify to various conditions as well as move from one channel to another without causing any mistake in transmission. This adaptable property is also needed to adapt to various bandwidths, modulation and coding schemes according to TVWS conditions [66]. The physical layer should be able to understand the dynamic nature of spectrum in TVWS. In [66], it is stated that the Radio Resource Control (RRC) and Radio Resource Management (RRM) layers in LTE UE need to be able to support the dynamic configuration of bandwidth based on the availability of white space as well as include the appropriate algorithms for choosing among various white space spectrum that may be available in its specific location.

4.4 TV White Space in Australia

Australia's digital switch-over was completed on December 2014. TVWS spectrum in Australia lies in the frequency range where the restacking of digital terrestrial television is done [6]. TVWS vary according to the geographical location and time.

4.4.1 White spaces and channel planning

After the completion of digital switchover in Australia in December 2014 digital terrestrial television operates mainly in 520-694 MHz frequency range [12]. Most licences areas, and particularly metropolitan areas, require at least six main transmitter channels. Australia because of its large size and low population (concentrated in metropolitan areas), Australia should plan its channels on a noise-limited basis rather than the interference-limited basis (which is often necessary in more densely populated countries such as the USA or the UK) [59]. This is essentially a reflection of the discretion afforded by the much smaller number of metropolitan areas in Australia, relative to most other industrialised countries. Although the same general principle applies to both noise limited and interference limited planning models, noise limited channel planning create much larger white spaces because the frequency reuse distances are larger than those used in an interference-limited approach [59].

4.4.2 White Space Arrangements

Freyens and Loney [59] explained in their studies that Australia has long established arrangements that have enabled the co-existence of broadcast services (authorised by apparatus licences) and symbiotic WSD (authorised by class licences) in the UHF spectrum from 520-820 MHz used for terrestrial television services. This coexistence arrangement only requires the mildest type of regulatory interventions: a standard secondary usage easement for class licensed (unlicensed) usage is all that is necessary. These arrangements are commonly provided for in ITU-R allocations and then implemented in different countries through national licensing regimes. Such easements can also be crafted in such a way as to specify the rules establishing settlement area for invasive WSDs. If broadcast spectrum is indeed large enough to accommodate both types of services or tolerate these kinds of subdivisions then the regulatory choices are relatively simple. However, the age of large spectrum allocations to terrestrial broadcasters is quickly receding, constraining regulatory choices for white space usage [59].

According to Australian Communications and Media Authority (ACMA formerly ACA)[61], the class licence for low interference potential devices (the LIPDs class licence) authorises the operation of low powered wireless microphones up to 3 mW EIRP, through provisions for wireless audio transmitters in the radio-frequency spectrum between 174 - 230 MHz and 520 - 820 MHz (VHF TV channels 6 to 12 and UHF TV channels 28 to 69, respectively). A WSD may be operated in any TV channel from this suite that is not used for television broadcasting in the same area. Higher powered wireless microphones up to 50 mW transmitter power may be authorised to operate in these bands under the ACMA apparatus licensing regime, subject to the same deployment constraints. In Australian context, VHF TV channels 6, 8, 9A, 11 and 12 are not been used in metropolitan areas and is occupied by VHF wireless microphone for many years [61].

4.5 Interference Analysis from LTE TDD to DVB-T in TV White Space

LTE FDD system transmission uses different frequency spectrum for both uplink and downlink. However, LTE TDD uses a same frequency spectrum for both uplink and downlink. In LTE TDD it is possible to change the LTE uplink and downlink capacity ratio according to the need. Whereas, in LTE FDD uplink and downlink capacity is determined by frequency allocation by regulatory authorities which make it difficult to make dynamic changes [67]. So LTE TDD is an important solution which can operate in TVWS with much wider bandwidth and throughput. In our study we have considered LTE TDD as the cognitive technology to operate in TVWS.

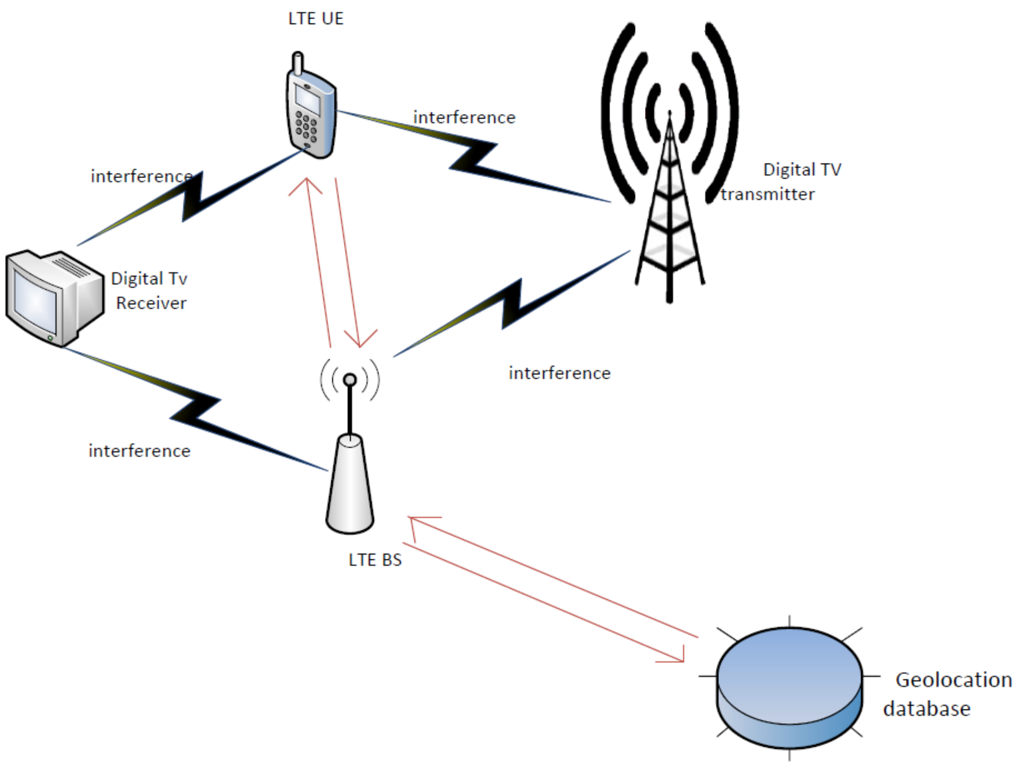

Figure 4.2: Interference scenerio when LTE TDD operates in TV White Space

When LTE TDD operates in TVWS it may cause harmful interference to primary users which are DVB-T. Figure 4.2 shows the scenario where LTE TDD UE and BS cause interference to DVB-T transmitter and receiver when operating on adjacent channel in TV white space.

4.5.1 Interference Analysis Method

We use the Interference Analysis Method to estimate the minimum separation distance between DVB-T and LTE TDD operating in TVWS. The total interference from LTE TDD system to DVB-T can be expressed as [36]:

$$I_{LTE-TDD} = P_t + G_{tr} + G_{re} - ACIR - PL \tag{4.1}$$

where, $I_{LTE-FDD}$ = total channel interference received from LTE TDD,

P_t = Transmit power of LTE TDD system,

G_{re} = DVB-T receiver antenna gain,

G_{tr} = LTE TDD antenna gain,

PL = the propagation path loss between DVB-T receiver and LTE TDD.

Adjacent channel interference ratio ($ACIR$), is the total interference between adjacent channels. $ACIR$ will depend solely on adjacent channel selectivity (ACS) and adjacent channel leakage ratio ($ACLR$) performance numbers. It can be expressed as [36]:

$$\frac{1}{ACIR} = \frac{1}{ACS} + \frac{1}{ACLR} \tag{4.2}$$

In the case of uplink, $ACLR_{UE} << ACS_{BS}$ as the UE transmitter is the limiting design factor which dominates the uplink interference. So in an uplink simulation

$ACIR \approx ACLR_{UE}$ where UE $ACLR$ performance is simulated [40].

In the case of downlink, $ACS_{UE} << ACLR_{BS}$ as the UE receiver is the limiting design factor which dominates the downlink interference. So in downlink simulation $ACIR \approx ACS_{UE}$ where UE ACS performance is simulated [40].

$ACIR$ can be calculated using guard bands which is expressed as [41]

$$ACIR = P_{inband} - 10\log_{10}[P_t \times BW(10^{(-1.8 \times G + 10^{-4}})] \tag{4.3}$$

where, P_{inband} is the power of operating band in dBm,
G is the guard band,
P_t is the transmitting power in mW,
BW is the bandwidth in MHz.

To prevent interference from LTE TDD to DVB-T, the interfering signal power should be controlled as the following inequality [36]:

$$I_{LTE-TDD} < I_{th} \tag{4.4}$$

where, I_{th} is the interference threshold of LTE TDD transmitter of BS or UE and is taken to be an I_{th}/N value of 6 dB [37].

To satisfy $I_{LTE-TDD} < I_{th}$, it needs to maintain a minimum distance or isolation between DVB-T and LTE TDD BS or UE.
The receiver noise which is expressed as N can be obtained as follows [36]:

$$N = -174 + 10\log_{10}(BW) + NF \tag{4.5}$$

where, BW is the LTE TDD bandwidth and NF is the noise figure.

When the distance between DVB-T transmitter and LTE TDD BS or UE is fixed, additional isolation should be guaranteed to protect DVB-T from the interference signal of LTE TDD, which can be expressed as follows [36]:

$$I_{LTE-TDD} - I_{add} < I_{th} \tag{4.6}$$

ACS is a measure of receivers ability to receive a signal at its assigned channel frequency in the presence of modulated signal in the adjacent channel. ACS is calculated using the power of wanted signal and maximum power of interference under a fixed bit error rate of receiver measured in the test which is obtained as follows [36]:

$$\frac{P_{refsen}}{N_t} = \frac{P_{refsen} + \triangle s}{N_t + 1/ACS} \tag{4.7}$$

where, P_{refsen} is sensitivity power level,

N_t is thermal noise of receiver and

$\triangle$s is the ratio of wanted signal power to receiver sensitivity.

Path loss (PL) is expressed in dB. The path loss can be calculated using the formula

[36]:

$$PL = 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(H_{BS})a(H_{UE}) + [44.9 - 6.55\log_{10}(H_{BS})]\log_{10}(d) \tag{4.8}$$

where,

$$a(H_{UE}) = [1.1\log 10(f) - 0.7]H_{UE}[1.56\log 10(f) - 0.8], \tag{4.9}$$

d is the separation between transmitter and receiver ,

f is a centre frequency ,

H_{BS} = Base station antenna height,

H_{UE} = User station antenna height.

Now we can use (3.1) and (4.8) to determine the minimum separation distance (d_{min}) which provide the necessary isolation between DVB-T antenna and LTE FDD transmission. The resulting minimum separation distance can be expressed as:

$$d_{min} = 10^{\frac{(P_t + G_{tr} + G_{re} - ACIR - I_{LTE-TDD} - 69.55 - 26.16\log_{10}(f) + 13.82\log_{10}(H_{BS}) + a(H_{UE})}{[44.9 - 6.55\log_{10}(H_{BS})]}} \tag{4.10}$$

4.5.2 Interference Analysis Scenarios

LTE TDD can be utilized using 5 , 10 and 20 MHz bandwidth. Each channel in DVB-T transmission is of 7 MHz bandwidth. LTE TDD deployment in TVWS is possible if LTE TDD bandwidth is within unused DVB-T bandwidth. In order to study the best deployment of LTE TDD in TVWS, we first study four possible cases.

1. Case I

   In this case we have considered TVWS as one DVB-T channel which is of 7 MHz in Australia. We have assumed LTE TDD of 5 MHz bandwidth operating on this TVWS with the guard band of 1 MHz which is shown in Figure 4.3.

Figure 4.3: Case I - LTE TDD 5 MHz operating on one free channel

2. Case II

   In this case we have considered TVWS as two contiguous DVB-T channels which is of 14 MHz. We have assumed LTE TDD of 5 MHz bandwidth operating on this TVWS with the guard band of 4.5 MHz which is shown in Figure 4.4.

Figure 4.4: Case II - LTE TDD 5 MHz operating on two contiguous free channels

3. Case III

   In this case we have considered TVWS as two contiguous DVB-T channels which is of 14 MHz. We have assumed LTE TDD of 10 MHz bandwidth operating on this TVWS with the guard band of 2 MHz which is shown in Figure 4.5.

Figure 4.5: Case III - LTE TDD 10 MHz operating on two contiguous free channels

4. Case IV

   In this case we have considered TVWS as three contiguous DVB-T channels which is of 14 MHz. We have assumed LTE TDD of 10 MHz bandwidth operating on this TVWS with the guard band of 5.5 MHz which is shown in Figure 4.6.

Figure 4.6: Case IV - LTE TDD 10 MHz operating on two contiguous free channels

4.5.3 Results

When minimum transmit power is used, the highest minimum separation distance that we can observe is 0.33 cm which was in Case I. If the minimum transmit power is used, we will observe acceptable minimum separation distance in all cases. As such we will be analysing the cases using maximum transmit power. In Table 4.1 the results of Case I, II, III and IV are shown, which are calculated using maximum LTE TDD transmit power. In Case I, 5 MHz LTE TDD bandwidth is operating with the guard band of 1 MHz has the minimum separation distance of 288.8 m for UE and 12.86 km for BS. In Case II, 5 MHz LTE TDD bandwidth is operating with the guard band of 4.5 MHz has the minimum separation distance of 6.09 m for UE and 0.271 km for BS. In Case III, 10 MHz LTE TDD bandwidth is operating with the guard band of 2 MHz has the minimum separation distance of 95.91 m for UE and 4.27 km for BS. In Case IV, 10 MHz LTE TDD bandwidth is operating with the guard band of 5.5 MHz has the minimum separation distance of 1.87 m for UE and 0.108 km for BS. The results of Case I and III show the requirement for high separation distance, so those proposed band plan may not be suitable case for deployment. However, Case II and IV show less minimum separation distance so this proposed band plan is acceptable. From the results of Case I, II, III and IV we can conclude that with the increased guard band, the minimum separation distance is less.

Table 4.1: Minimum Separation between LTE TDD UE or BS and DVB-T in TVWS for Case I, II, III and IV using Maximum Transmit Power

		Minimum Separation Distance			
		Case I	Case II	Case III	case IV
		Guard band 1 MHz	Guard band 4.5 MHz	Guard band 2 MHz	Guard band 2 MHz
User Equipment (UE)	Rural	347.04 m	7.32 m	115.25 m	2.43 m
	Urban	288.8 m	6.09 m	95.91 m	1.87 m
Base Station(BS)	Rural	15.46 km	0.326 km	5.13 km	0.243 km
	Urban	12.86 km	0.271 km	4.27 km	0.108 km

4.5.4 Case Study On Sydney Region

Now we consider Sydney region (Sydney North West, Sydney South West, Sydney, Manly, Kingscross, Mosman) which is the proposed Channel allotments for digital TV by ACMA [68]. In Sydney region, there is a continuous free or unused six channels from Channel 34 to Channel 39 as shown in Figure 4.7. The unused six channels is of 42 MHz spectrum. There are many other unused spectrum which vary according to the geographical location apart from the continuous unused six channels as shown in Figure 4.7. This unused spectrum can be utilised for operating LTE TDD of bandwidth 1.4, 3, 5, 10, 20 MHz based on the available free spectrum.

Area Served	Pol	6	7	8	9	9A	10	11	12	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Wyong[3]	V																					SBS	ABC	ATN	TCN	TEN	UA	NEN	NBN	NRN			
Gosford3	H																					SBS	ABC	ATN	TCN	TEN	UA	NEN	NBN	NRN			
Bouddi3	V																					SBS	ABC	ATN	TCN	TEN	UA	NEN	NBN	NRN			
Sydney North West	H									ATN	UA	ABC	TEN	SBS	TCN																		
Sydney	H	ATN	SBS	TCN		DAB	UA	TEN	ABC		TSN																						
Manly/Mosman	H									ATN	UA	ABC	TEN	SBS	TCN																		
Kings Cross	H									ATN	UA	ABC	TEN	SBS	TCN																		
Megalong	V																											ATN	TCN	TEN	ABC	SBS	UA
Woronora	V																					SBS	ABC	ATN	TCN	TEN	UA						
Sydney South West	H																					SBS	ABC	ATN	TCN	TEN	UA						
Picton	V																					SBS	ABC	ATN	TCN	TEN	UA						

Figure 4.7: Proposed channel allotments for Sydney region [68]

Based on the results (Table 4.1) of case I, II, III and IV, it is clear that increasing the guard band reduces the interference to the adjacent channel. Considering the outcome of above cases we propose two deployments for the free six channels in Sydney region which are shown in Figure 4.8 and Figure 4.9. The goal of these deployments is to provide high data rate LTE TDD system within TVWS spectrum.

In deployment 1, the TVWS of 42 MHz is used by LTE TDD of 20 MHz bandwidth which has the guard bands of 11 MHz each. The green part shows the guard band of 11 MHz each and red part shows LTE TDD of 20 MHz bandwidth.

Figure 4.8: Deployment 1- Makeup of LTE TDD in TV White Space with 11 MHz Guard Band

In deployment 2, the TVWS of 42 MHz spectrum is allocated for 10 MHz and 20 MHz LTE TDD bands with 4 MHz guard band as shown in Figure 4.9. The green part shows three guard band of 4 MHz each, red part shows LTE TDD of 20 MHz bandwidth and the blue part with LTE TDD of 10 MHz bandwidth.

4.5.5 Results Of Case Study In Sydney Region

The calculations for the deployment 1 in TVWS for Sydney region was done using maximum transmit power for both UE and BS and with 11 MHz Guard Band. The minimum separation distance for UE's are 0.57 cm for rural area and 0.47 cm for urban

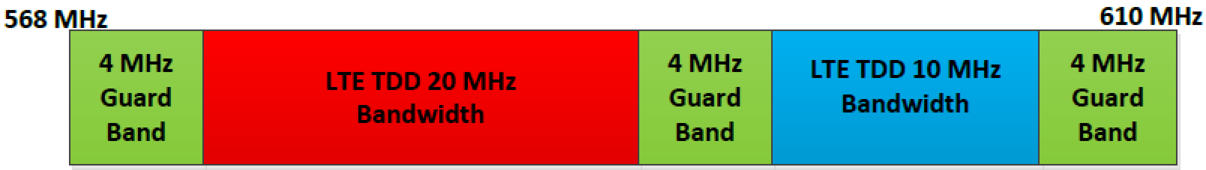

Figure 4.9: Deployment 2- Makeup of LTE TDD in TV White Space with 4 MHz Guard Band

area. Whereas, the minimum separation distance for BS's are 25 cm for rural area and 21 cm for urban area. The minimum separation for both UE is really low so deployment 1 can be applicable in TVWS.

Table 4.2 shows the minimum separation distance between LTE TDD system for both minimum and maximum transmit power in urban and rural area with 4 MHz Guard Band. With the minimum transmit power the minimum separation distance for rural area is 0.57 cm and 0.47 cm for urban area. However, with the maximum transmit power the minimum separation distance for rural area is 12.71 cm and 10.57 cm for urban area.

Table 4.2: Minimum Separation between LTE TDD UE and DVB-T in TVWS for Deployment 2

		Minimum Separation Distance	
		LTE BW 10 MHz	LTE BW 20 MHz
Maximum Transmit power	Rural	12.71 cm	12.71 cm
	Urban	10.57 cm	10.57 cm
Minimum Transmit Power	Rural	0.57 cm	0.57 cm
	Urban	0.47 cm	0.47 cm

Table 4.3 shows the minimum separation distance for deployment 2 between LTE TDD BS

and DVB-T when operating on TVWS. The minimum separation distance is calculated for both minimum and maximum transmit power of LTE TDD BS in urban and rural area. With the minimum transmit power the minimum separation distance for rural area is 0.0073 cm and 0.0061 cm for urban area. However, with the maximum transmit power the minimum separation distance for rural area is 566.44 m and 471.37 m for urban area.

Table 4.3: Minimum Separation between LTE TDD BS and DVB-T in TVWS for Deployment 2

		Minimum Separation Distance	
		LTE BW 10 MHz	LTE BW 20 MHz
Maximum Transmit power	Rural	566.44 m	566.44 m
	Urban	471.378 m	471.378 m
Minimum Transmit Power	Rural	0.0073 cm	0.0073 cm
	Urban	0.0061 cm	0.0061 cm

4.6 Summary

In this chapter, a study on interference from TVWS devices to DVB-T receivers was presented considering LTE TDD as the secondary user. Minimum separation distance was calculated for LTE TDD and DVB-T in TVWS using minimum and maximum transmit power levels for both UE and BS. Based on the results from the calculations we can suggest that LTE TDD can operate on TVWS when the LTE TDD transmission is done with less transmit power. Minimum separation distance increases with the increase in transmit power. However, the minimum separation distance decreases in the presence of large guard band.

Chapter 5

Conclusions

The switchover from analog TV to DVB-T freed some unused spectrum called digital dividend. Digital dividend is utilised for the deployment of LTE FDD system where uplink and downlink are at two different frequency bands. When LTE FDD operates on digital dividend LTE FDD may cause unwanted interference on DVB-T. In Australia conventional duplex arrangement is the preferred approach for allocating LTE FDD in digital dividend where uplink lies in lower part and downlink on higher part.

There are some unused spectrum in the spectrum for DVB-T broadcasting which is called TVWS. TVWS can be utilised by secondary users to solve the spectrum scarcity issue. In this thesis we have considered interference from secondary users on DVB-T receiver. LTE TDD is considered as secondary user in our study as both uplink and downlink are in the same frequency as they are more flexible than LTE FDD. Our study is done in Sydney region TVWS to calculate the interference from LTE TDD to DVB-T.

5.1 Summary and Conclusions

In this thesis we focus on the interference from LTE system to DVB-T when operating on both digital dividend and TVWS. In Chapter 3 Interference analysis method and Monte Carlo Simulation method is used to calculate the interference from LTE FDD to Channel 51 of DVB-T with the presence of a guard band of 9 MHz. Interference analysis was used to calculate the minimum separation between LTE FDD and DVB-T to avoid the interference from LTE FDD to DVB-T. Outage probability analysis was used to calculate the probability of location within the considered area that suffer maximum level of interference. The results show that with increased guard band the separation distance between LTE FDD UE or BS and DVB-T reduces the interference between adjacent channels. The results of our study show that there is a minimum interference onto DVB-T reception on channel 51 when LTE FDD system is operating on adjacent channel in digital dividend spectrum with 9 MHz guard band.

TVWS studies has been done by FCC in United States and by Ofcom in Europe, however no major studies has been done in Australia for the impact of operating WSD in TVWS. It was shown that LTE TDD is the better candidate to be TVWS device compared to LTE FDD as both uplink and downlink lies on the same frequency band. LTE TDD is taken as WSD in our study as both uplink and downlink lies in same frequency which helps LTE TDD to use TVWS more effectively. TVWS spectrum varies with location and time. We have considered Australian DVB-T transmission in our study. It was shown that increasing the guard band reduces the interference to adjacent channel. Minimum separation distance between LTE TDD and DVB-T is calculated in Chapter 4 using minimum and maximum transmit power.

5.2 Future Work

This section provides recommendations for possible directions for future research based on the outcomes of this thesis.

- In the current work interference on DVB-T receivers was studied using a transmission from single UE. This study can be extended for multiple UEs operating on adjacent to the DVB-T channel 51.
- Interference study on TVWS is done using in Sydney Region. As Australia is large country studies can be done on different regions by identifying the TV white spaces.
- Interference analysis method is used in this thesis to calculate the minimum separation distance between LTE TDD and DVB-T. The probability of location within the coverage area of DVB-T that will suffer unacceptable level of interference from LTE TDD when operating in TV White Space can also be calculated.
- LTE TDD is considered in this thesis as WSD to study interference to primary users. Nevertheless, interference study can be also performed in TVWS with other applications such as IEEE 802.11af.

Bibliography

[1] Australian Government Switchover Taskforce, Technical advisory note for multi-dwelling units and other buildings with Master Antenna Television (MATV) systems, *Technical Advisory Note: TAN31, Australian Digital Testing,* May 2012.

[2] CEPT Report 30, The identification of common and minimal (least restrictive) technical condition for 790-862MHz for digital dividend in the European Union. *Electronic Communication Committee (ECC) within the European conference of Postal and Telecommunication Administration (CEPT),* 30 October 2009.

[3] ITU-R Document 5-6/84-E, Detailed results of field study of compatibility between DVB-T and UMTS European Broadcasting Union / Free TV Australia Ltd., *International Telecommunication Union,* 6 May 2009.

[4] Technical analysis of interference from mobile network base station in 800 MHz band to digital terrestrial television, tech. rep., Ofcom, Jun. 2011.

[5] B.Modlic, G.Sisul, M.Cvitkovic, Digital dividend-Opportunities for new mobile services. *University of Zagreb,Faculty of Electrical engineering and Computing,* 2009.

[6] Digital Dividend Green Paper, *tech. rep., Department of Broadband, Communications and the Digital Economy, Australia,* 2010.

[7] ACMA, Digital dividend auction timing, *Retrieved in 10 May 2013, from http://http://engage.acma.gov.au/digitaldividend/.*

[8] J. Butler, TV White Space Devices and Beyond, *Technology Director for Radio Spectrum Policy, Ofcom,* 1011.

[9] Australian Broadcasting Corporation, Digital Dividend Green Paper, *submission to The Australian Government,* 2010.

[10] What is DVB-T, *Retrieved in 1 December 2014. from http://www.radio-electronics.com/info/broadcast/digital-video-broadcasting/what-is-dvb-t-basics-tutorial.php.*

[11] Digital Video Broadcasting, A guideline for the use of DVB Specifications and standards, *DVB document A020 Rev.1,* 2000.

[12] Digital Terrestrial Television Broadcasting Planning Handbook, *Australian Broadcasting Authority, Canberra,* 2005.

[13] Parameters for LTE-Advanced and wirelessman advanced for use in sharing studies,*Radiocommunication study groups, International Telecommunication Union,* October, 2012.

[14] Technical planning parameters and methods for terrestrial broadcasting, *Australian Broadcasting Authority,* 2004.

[15] E.Dahlman, H.Ekstrm, A.Furuskr, J.Karlsson, M.Meyer, S.Parkvall, J. Torsner , M. Wahlqvist, The long-term evolution of 3G. em Ericsson Review no 02, 2005.

[16] Farooq Khan, LTE for 4G mobile Broadband, *Air Interface Technology and Performance*, 2009.

[17] T. Eyers, LTE overview - An Australian Perspective. *TEKTEL,* 2011.

[18] R. Surgiewicz, N. Strom, A. Ahmed, Y. Ai, LTE uplink transmission scheme, *Chalmers University of Technology, Dept. of signals and system.*

[19] B. Hanta, SC-FDMA and LTE uplink physical layer design, *Ausgewahlte Kapitel der Nachrichtent,* 2009.

[20] N. Marchetti, M. Rahman, S.Kumar, R. Prasad, OFDM Principles and Chalenges.

[21] Time division duplex vs frequency division duplex in wireless backhauls, *NETKROM technologies.*

[22] I. Poole, LTE Frequency Bands and Spectrum Allocations. *Radio-electronics.com,* Retrieved 20 February 2015.

[23] T.S. Rappaport, Wireless Communications, *Principles and Practice, Prentice Hall,* 1996.

[24] S. Miah, M. Rahman, T. Godder, B. Singh, M. Parvin, Performance comparision of AWGN, Flat fading and frequency selective fading channel for wireless communication system using 4QPSK, 2011.

[25] W. Dally, J. Poulton, Digital Systems Engineering, *Cambridge University Press,* 1998.

[26] M. Vanston: Asia Pacific Telecommunity (APT) 700 MHz Whitepaper, *Networks, Telstra Operations*, 8 May, 2013.

[27] AWF-9/OUT-12, APT common views on harmonised frequency arrangements for IMT in the band 698-806MHz. *Asia-Pacific Telecommunity (APT),* 16 September 2010.

[28] AWF-9/OUT-13, Harmonized frequency arrangements for the band 698-806MHz. *Asia-Pacific Telecommunity (APT),* 16 September 2010.

[29] CEPT Report 23, Technical option for the use of harmonised sub-band in the band 470-862MHz for fixed/mobile application (including uplinks). *Electronic Communication Committee (ECC) within the European conference of Postal and Telecommunication Administration (CEPT),*21 December 2007.

[30] Time division duplex vs frequency division duplex in wireless backhauls, *NETKROM technologies.*

[31] A. Guidotti, M.Barbiroli, P. Grazioso, C. Carciofi, D. Guiducci, Analysis of coexistence and mutual interference between mobile and digital television systems, 2011.

[32] CEPT Report 31, Frquency (channeling) arrangements for the 790-862MHz band. *Electronic Communication Committee (ECC) within the European conference of Postal and Telecommunication Administration (CEPT),* 30 October 2009.

[33] W. Sami, How can mobile and broadcasting networks use adjacent bands, 2011.

[34] Measurement Of Protection Ratios and Overload Thresholds For Broadcast TV Receivers. ITU-R BT.2215-2, 2012.

[35] K. Sakic, S. Grgic, The influence of the LTE system on DVB-T reception, *Croatian Post and Electronic Communication Agency,* 2010.

[36] W. Wang, B. wang, Z. Lv, W. Huang, Y. Zhang, Analysis of Interference From Digital Terrestrial Television Broadcast To LTE TDD in Digital Dividend Spectrum, *Proceedings of IC-NIDC2010.*

[37] Recommendation ITU-R M.2039, Characte- ristics of terrestrial IMT-2000 systems for frequency sharing/interference analyses, *ITU,* 2009.

[38] I. Cho, I. Lee, Y. Park, Study on coexistence between Long Term Evolution and Digital Broadcasting Services, *International Journal of Advanced Science and Technology*, Vol.38, January, 2012.

[39] R. Liyanapathirana, U. Gunawardana, P. Wijesinghe and S. Biyanwilage, RF Interference to DVB-T Reception From UMTS/LTE Systems In Adjacent Bands,*IEEE Tencon-Spring*, 2013.

[40] S. Pike, Liaison statement to ERC TG1,*Technical Specification Group, RAN Meeting 3,* April 1999.

[41] J. W. Jung, D. S. Kim, D. G. Cho, Y. S. Kim, Required guard band for coexistence LTE/FDD systems obtained by Accurate analysis of Adjacent Channel Interference, *Journal of Electromagnetics wave and Applications,* April 2012.

[42] "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (release 10),"TS 36.101V10.3.3, 3GPP, Jun, 2011.

[43] W.A. Hassan, Y. Abdulrahman, T.A. Rahman, The Digital dividend spectrum in Asia, *Wireless Communication Center, University Technology Malaysia,* 2012.

[44] D.H. Kim, S.J. Oh, J. Woo, Coexistence Analysis between IMT system and DVB-T system in 700MHz, 2012.

[45] A. Aloisi, M.Celidonio, L.Pulcini, A.Rufini, Experimental study on protection distance between LTE and DVB-T stations operating in Adjacent UHF Frequency bands. *Fondazione Ugo Bordoni,* 2011.

[46] S. Sangtarash, H. Sadeghi, W.A.Hassan, H.L.King, T.A. Rahman, Using Cognitive radio interference mitigation technique to enhance coexistence and sharing between DVB-T and LTE system. *Future Network and Mobile Summit,* 2012.

[47] W.Li, J.Chen, H.Long, B.Wu, Performance and analysis on LTE system under Adjacent channel interference of broadcasting system. *Wireless signal Processing and network lab,* 2012.

[48] W. Dally, J. Poulton, Digital Systems Engineering, *Cambridge University Press,* 1998.

[49] E.Zanoio, S.Urvik, CDMA network technologies, *Monitoring and protocol test, Tektronix, Inc.*

[50] Time division multiple access applicable for mobile satellite communications, *Durban University of Technology,* 2011.

[51] N. Zurutuza, Cognitive Radio and TV White Space communication, *Norwegian University of Science and Technology,* 2011.

[52] K.H. Chang, IEEE 802 standards for TV White Space, *IEEE Wireless Commuincation,* 2014.

[53] G. Naik, S. Singhal, A. Kumar and A. Karandikar, Quantitative Assesment Of TV White Space in India, *Indian Institute Of Technology Bombay,* 2014.

[54] A.B Flores, R. Guerra, E. Knighty, P.Ecclesine and S. Pandey, IEEE802.11af: A Standard For TV White Space Spectrum Sharing, *IEEE Communications Magazine,* 2013.

[55] C.S. Sum, G.P. Villardi, M.A. Rahman, T. Baykas, H.N. Tran, Z. Lan, C. Sun, Y. Alemseged, Y. Wang, C. Pyo, S. Filin, H. Harada, Cognitive Communications in Tv White Spaces: An overview of Regulations, Standards and Technology, *IEEE Communications Magazine,* 2013.

[56] T. Baykas, M. Kasslin, M. Cummings, H. Kang, J. Kwak, R. Paine, A. Reznik, R. Saeed,S. Shellhammer, Developing a standard For TV White Space Coexistence: Technical Challenges and Solution Approaches, *IEEE Wireless communications,* 2012.

[57] A.K. Sadek, Interference Management In TV White Space, *Corporate Research and Development, Qualcomm Incorporated, San Diego,* 2010.

[58] E. Obregon, L. Shi, J. Ferrer,J Zander, A Model for Aggregate Adjacent Channel Interference in TV White Space, *2Center for RF Measurement Technology, Hogskolan i Gavle, Gavle, Sweden,* 2011.

[59] B.P . Freyens, M. Loney, Land of white space opportunity: channel planning and DTV restack in Australia, *info, Vol. 13 Iss 4 pp. 30 - 41,* 2011.

[60] Wireless microphones- Getting Ready for 1 January 2015, *Australian Communication and Media authority,* 2014.

[61] WIRELESS MICROPHONES and DIGITAL TELEVISION/DATACASTING, FINDINGS PAPER, *Radiofrequency Planning Group, Australian Communications Authority,* 2000.

[62] J. Mitola. and G.Q. Maguire, Cognitive radio: making software radios more personal, *Personal Communications, IEEE,*, 1999.

[63] T.Yuseyin, H. Arslan, A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications,*IEEE communications survey and tutorials*, 2009.

[64] A. Khattab, D. Perkins, M. Bayoumi, Cognitive Radio Networks From Theory To Practice,*Springer*.

[65] X. Lin, Y. Fang, G. Wei, D. Zhang, Compatibility analysis between cognitive radio and DVB-T system. *Beijing key of intelligent telecommunications software and multimedia,* 2009.

[66] P.Surampudi, LTE-Advanced in White Space A Complementary Technology, *Radisys White Paper,* December 2011.

[67] TD-LTE White Paper, *Nokia Siemens Network*, 2010.

[68] Engineering Report restack Channel Planning sydney, *Australian Communication and Media Authority,* Sept 2012.

[69] Recommendation ITU-R BT.1368-8, Planning Criteria for digital terrestrial television services in the VHF/UHF bands, *ITU,* 2009.